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TERRAIN CONSTRAINTS ON THE DESIGN, TESTING, AND DEPLOYMENT OF THE GATOR MINE

by

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Final Report

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The GATOR mine system consists of two look-alike, air-delivered, target-activated mines. The antitank/antivehicle (AT/AV) mine uses a magnetic sensor, and the antipersonnel (AP) mine utilizes a seismic sensor.

Tests of The GATOR mine ~~system has been tested~~ in various terrains within the United States. ~~These tests~~ indicated that a non-uniform sensitivity existed in ~~the GATOR~~ its AP ~~mine~~ seismic sensor. It was demonstrated that soil characteristics can

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20. ABSTRACT (Continued) $\rightarrow$ of p1473A)

affect sensor sensitivity, causing the mine to detonate when the target is beyond warhead lethal range, or causing it not to detonate at all. Thus, its effective use is restricted.

Using computer models that were validated through field studies, this report attempts to predict the expected sensitivity of the GATOR AP seismic sensor. A terrain matrix, made up of elements describing surface and subsurface terrain layers that affect target-induced seismic signal generation and propagation, was developed to define environmental parameter variation. Computer model signals were generated using the matrix results for input to the GATOR mine logic. The results were utilized to define mine performance changes over the environmental parameter ranges. Terrain property combinations which have major effects on source-to-ground energy coupling and seismic signal propagation were evaluated using ~~U. S.~~ Army Engineer Waterways Experiment Station (WES) micro-seismic generation and propagation models. The models were validated to verify if they could realistically predict, with sufficient sensitivity and reliability, time domain signals versus terrain characteristics. Model validation data were obtained at WES, Vicksburg, Mississippi; Eglin AFB, Florida; Honeywell, Inc., Hopkins, Minnesota; and Nellis AFB, Nevada. The data collected included:

a. HS-10 scientific geophone footstep analog signals.

b. Ground compression and shear wave velocities from refraction seismic surveys.

c. Moisture content, density, and grain-size distribution versus soil depth.

d. Cone index versus soil depth.

e. Surface rigidity.

Predicted digital signals were converted to analog signals and interfaced with the GATOR mine logic at the geophone attachment point. Mine operation was then monitored for similarity with field tests, thus demonstrating a new procedure for defining seismic sensor operational limitations.

1473B

PREFACE

This study was conducted by personnel of the Mobility and Environmental Systems Laboratory, U.S. Army Engineer Waterways Experiment Station, P.O. Box 631, Vicksburg, Mississippi 39180 during the period from December 1973 to September 1974. It was funded by Military Interdepartmental Purchase Request (MIPR) Nos. FY7621-74-90051, FY7621-74-90082, FY7621-74-90118, and FY7621-75-90012, dated 15 November 1973, 5 March 1974, 21 May 1974, and 12 July 1974, respectively, from the Armament Development and Test Center, Eglin Air Force Base, Florida 32542, under the GATOR Mine Program. Mr. Francis D. Irby, Jr. of the Air Force Armament Laboratory (DLJM) monitored the program.

This study was under the general supervision of Messrs W. G. Shockley, Chief, Mobility and Environmental Systems Laboratory (MESL), and W. E. Grabau, Special Assistant, MESL (formerly Chief of the Environmental Systems Division (ESD)). Mr. B. O. Benn, Chief, Environmental Research Branch (ERB), ESD, directed the study with the assistance of Mr. J. R. Lundien. Mr. P. A. Smith, ERB, had the responsibility for the field tests, and Mr. E. A. Baylot, ERB, had responsibility for the computer exercise. Other WES personnel making significant contributions to this study were Mr. E. E. Garrett, Mr. B. T. Helmuth, and SP4 J. Eggleston, formerly of ESD.

Acknowledgement is made to Messrs. C. B. Simpson and E. J. Lindsey, Jr., GATOR Program Office, Eglin Air Force Base, and to Mr. C. P. Varecka of Honeywell, Inc., Hopkins, Minnesota, for their advice and technical assistance during the study.

The Director of WES during the study and preparation of this report was Colonel G. H. Hilt, CE. The Technical Director was Mr. F. R. Brown.

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

Neal L. Funston

NEAL L FUNSTON, Lt Colonel, USAF
Deputy Director, Munitions SPO
Deputy for Armament Systems

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SECTION I

BACKGROUND

The Gator mine system consists of two visually indistinguishable mines, an antitank (AT) mine activated by a magnetic sensor and an antipersonnel (AP) mine activated by a seismic sensor. The mines are delivered by both rotary- and fixed-wing aircraft. The Gator mine system is currently undergoing engineering development in a triservice program under the direction of the "Joint Development Plan, Air-Delivered Antipersonnel and Anti-Vehicular Target Activated Munition Systems."

The Gator mine system has been tested in many different areas in the United States. One important result from these tests is the nonuniform sensitivity of the seismic sensors for the AP mines in all terrains. Sometimes the sensor will cause a mine to detonate too soon (i.e.,the range of detection is beyond the lethal range of the mine), and sometimes a mine will not detonate at all. Ideally, of course, the mine should always function within the lethal radius of the mine for a walking-man target, regardless of local site conditions. Unfortunately, the seismic response from a man walking varies as a function of terrain conditions, and this affects the performance of the mine.

SECTION II

PROBLEMS CAUSED BY NONHOMOGENEOUS MATERIALS

The ability of the soil to propagate seismic, or vibratory, energy is widely variable and depends on several factors. Soils with their very wide range of textures varying from unconsolidated sands through silts to fat clays, all with varying mixtures, degrees of consolidation, and moisture contents, generally exhibit seismic propagation properties that fall within acceptable limits for at least some seismic sensor designs. However, when soils are frozen, their rigidity increases abruptly. This not only may mask the distinction between layering, or zones of different density (provided the frozen condition is sufficiently deep), but also creates a condition in which the seismic velocities, particularly those associated with the higher frequencies of the signal, increase markedly with a corresponding decrease in amplitude. Under such conditions the energy reaching the sensor may be too small or too distorted by frequency filtration to provide a detectable signal above background noise.

Furthermore, a significant portion of the land-mass surface of the earth is rock, either underlying a thin soil mantle or directly exposed. Where the surficial mantle is not more than approximately 1 m deep, seismic energy is propagated in a manner similar to that described above, i.e., the wave forms may be distorted and the amplitudes may be small. Such surfaces are most commonly encountered in rugged mountainous areas and in deserts where the lack of precipitation has produced very thin soils and wind scour has tended to remove much of the natural soil.

At the other extreme from the excessively rigid substances are such unconsolidated surface materials as dry, noncohesive sand or gravel. Such materials are found in sand dunes, are extensive in many desert areas, and along sea or lake strands. To some extent, loose, dry, surface soils (not necessarily sands) like those found in recently cultivated grounds may approximate the situation prevailing in loose

sands. In such unconsolidated substrate conditions, two phenomena deleterious to seismic energy propagation may occur:

1. The efficiency of the target-to-ground coupling may be severely reduced, so that little energy is actually coupled to the ground.
2. The amplitudes of the high-frequency components of the signal propagating from source to sensor may be markedly reduced.

Both these phenomena would tend to reduce the overall system sensitivity.

Other soil types, notably those in which large stones and boulders are embedded in a matrix of relatively fine-grained material, are also characterized by poor seismic wave propagation. Such soils are especially common in regions that have been subjected to glaciation. A typical and frequently found example is glacial drift; it is formed at the melting margin of glaciers when the contained rock and soil debris is deposited with little or no sorting or stratification. Nonhomogeneous soils of this type may be found in ridges (terminal moraines) or in undulating sheets (ground moraines). In some regions, such as in the northeastern and northcentral United States, the matrix may be dominantly clay (the so-called boulder-clays); whereas, in northern Europe the matrix is often silty or sandy. Other nonhomogeneous soils originating in association with glaciers are those forming drumlins (streamlined hills of glacial drift), eskers (sinuous ridges of sand, gravel, and boulders), and outwash plains (nearly flat or gently inclined plains formed of poorly sorted but stratified sand, clay, gravel, and boulders).

These landforms and their component nonhomogeneous soils may occur in any region that has been glaciated. However, by no means all soils originating in association with glaciers are nonhomogeneous; deep and homogeneous deposits of clay, silt, and sand soils are common and widespread. Furthermore, except for such special cases as eskers, the topographic expression is not a reliable indicator of soil homogeneity. About 25 percent of the land surface of the earth has been glaciated in

the recent geological past, and such soils are still in the process of formation at the edges of existing glaciers.

Other nonhomogeneous soils consisting of boulders and cobbles in matrices of sand, gravels, and clays are found in alluvial fans and talus slopes. Alluvial fans are common in places where mountains abut on plains or intermontane basins. Here rock detritus is carried by often torrential streams and deposited in sloping aprons on the mountain margins. Sorting of the component particles is poor. Talus slopes are made up of rock debris, carried principally by gravity, deposited on the lower margins of declivitous slopes. They are entirely heterogeneous mixtures of rock debris with no sorting or stratification.

All of these heterogeneous substrates affect seismic signal transmission in a similar manner. The energy attenuates much more rapidly than in a homogeneous material of comparable density. The effect is greater on high-frequency signals than on low. Consider, for example, a fine sand (which by itself efficiently propagates low frequencies) containing large rocks. With a broad-spectrum signal (e.g., that produced by an impuslive source, such as a footstep), the high-frequency components are filtered out in the sand and the low frequencies are attenuated by destructive interference because the waves have multiple path lengths as they pass around the large rocks. The result is a marked reduction in amplitude at the sensor.

Another condition, fortunately less common, is the occurrence of secondarily formed, hard, rock-like layers high in the soil profile. One such type is represented by "caliche," found in semiarid regions everywhere. A notable example in the southwest United States is found on the hilltops at Fort Hood, Texas. These soils are formed by the deposition of calcium carbonates concentrated in the upper layers of the soil by moisture drawn upwards by capillary action. The dense, rock-like deposits may range from a few centimetres to more than a metre in thickness. Another sort of secondarily formed rocky crust is laterite (not to be confused with lateritic soil), whose origin is complex and

not fully understood. It is found in many tropical environments, particularly in Africa, India, Southeast Asia, and Australia where its occurrence is sporadic, but widespread. The rocky material varies from nodular masses embedded in the soil to massive stony beds of great lateral extent. These rock-like near-surface deposits affect seismic propagation in the same way as natural rock surfaces, boulders, or caliche.

In summary, extreme surface conditions that are generally unfavorable for the deployment of seismically activated mines of any design exist on all continents. However, between the extremes of excessive rigidity, insufficient cohesiveness or density, and heterogeneity lie most of the surface materials covering the land masses of the world. In general it can be assumed that mine sensors and logics can be designed that will operate effectively in all except the most extreme conditions.

SECTION III

APPROACH TO THE PROBLEM

Since terrain conditions are so important in seismic sensor operation, the combinations of terrain properties that have the greatest effect on both source-to-ground energy coupling and seismic signal propagation must be determined. This information can then be used to redesign the mine to make it less sensitive to terrain conditions. Two approaches can be identified to gather the needed data: Field tests can be performed to sample the seismic responses in many different areas of the world, or computer models that have been validated with a number of field studies can be exercised.

The decision was made at the Gator Program Office, Eglin AFB, to use computer models to generate seismic data. Microseismic generation and propagation models at the U. S. Army Engineer Waterways Experiment Station (WES) had demonstrated changes in signal amplitude and frequency characteristics that agreed quite well with signals measured in the field. In addition, a limited number of field tests with the Gator mine had identified some potential areas in which environmental characteristics produced widely varying detection performances. What remained was to validate the models, i.e., demonstrate that the models can predict time-domain signals as a function of terrain with sufficient sensitivity and reliability to allow realistic predictions of Gator mine performance.

SECTION IV

THE VALIDATION EFFORT

Data for validation of the models were obtained at four sites: one each at WES, Vicksburg, Mississippi; Eglin AFB, Florida; Honeywell, Inc., Hopkins, Minnesota; and Nellis AFB, Nevada. Data collected during these tests included:

1. Analog signals for footsteps from HS-10 scientific geophones.
2. Compression and shear wave velocities of the ground from refraction seismic surveys.
3. Moisture content, density, and grain-size distribution of the soil as a function of depth from laboratory analyses on soil samples.
4. Cone index as a function of depth, as measured with a cone penetrometer.
5. Surface rigidity, as measured with a plate-load device.

Along with the scientific geophone signals, analog signals from Gator mine geophones and alarm signals from the mine were recorded at the WES, Eglin, and Honeywell sites. The reduced data from the field tests required for the validation effort are given in Table 1.

Since the Gator mine lies on the surface of the ground (loosely coupled) when it is in operating position, it does not measure the seismic signals traveling in the ground with pure fidelity, i.e., some of the seismic frequencies are converted to electrical signals with lower amplitudes than those of other frequencies. The relation that can be used to mathematically convert the seismic signal traveling in the ground to the electrical signal from the Gator mine geophone has been designated as a mine transfer function. The mine transfer function was derived by comparing, on a frequency-by-frequency basis, footstep signals from the scientific geophones (calibrated in units of particle velocity) and the Gator mine geophone (calibrated in units of voltage). The final

equation for the mine transfer function obtained from data at a number of ranges at the first three validation sites is shown below.

$$TF = \frac{TF_\infty (if)^2}{(if)^2 + 42(if) + (42)^2}$$

where

TF = mine transfer function, volts/(cm*/sec)

TF_∞ = mine transfer function sensitivity (= 0.423), volts/(cm/sec)

$i = \sqrt{-1}$

f = frequency, Hz

The Gator mine geophone alone has a natural frequency of 24 Hz, a sensitivity of 0.0866 volt/(cm/sec), and a damping factor of 0.5. The mine transfer function for the Gator mine geophone in the case on the ground surface represents a high-pass system with a natural frequency of 42 Hz, a sensitivity of 0.423 volt/(cm/sec), and a damping factor of 0.5. Thus, it would appear that a considerable influence is exerted by the packaging and ground surface coupling (i.e, equivalent to an increase in natural frequency of nearly 100 percent and an increase in sensitivity of nearly 500 percent). A plot of the Gator mine transfer function magnitude normalized by the Gator mine geophone sensitivity is shown in Figure 1, presented as 20 log magnitude versus frequency.

By using the Gator mine transfer function to modify the WES predicted seismic signals from footsteps,[1,2,3] the signals as they would

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* A table of factors for converting metric (SI) units of measurements to U. S. Customary units is given on page 73.

appear at the terminals of the Gator mine geophone could be obtained. Signals were predicted using this scheme for all four validation sites in the following sequence:

1. Footstep sequence for +30 m to -30 m on a straight line where the zero point is 5 m away from the sensor at the closest point of approach (CPA). This is equivalent to a straight 60-m walk line that would take the walker to within 5 m of the sensor at the midpoint of the travel.
2. Footstep sequence for +30 m to -30 m on a 10-m CPA line.
3. Footstep sequence for +30 m to -30 m on a 20-m CPA line.
4. A 60-m walk path at a constant range of 5 m. This is equivalent to a circular walk line that would take the walker nearly twice around a 5-m-radius circle centered on the sensor.
5. A circular 60-m walk path at a constant range of 10 m.
6. A circular 60-m walk path at a constant range of 20 m.

These footstep signals were computed for a man weighing 77.1 kg and walking at a rate of approximately 90 steps/min with a stride length of 0.8 m.

The predicted digital signals were converted to analog signals at WES and recorded on magnetic tape. These tapes were sent to Honeywell, Inc., Hopkins, Minnesota, where the signals were injected into the Gator mine logic at the point where the geophone would normally be attached. The operation of the mine was monitored by Honeywell personnel and verified as being very similar to that in the actual field tests. Based on this information, the Gator Program Office authorized the study herein.

SECTION V

PURPOSE AND SCOPE OF THIS STUDY

A terrain matrix was developed to define the range of environmental parameters required for this study. Signals generated with the computer models, using the results from the terrain matrix, were input to the Gator mine logic, and the results were used to define the changes in performance of the mine over large ranges of environmental parameters. Details of these efforts are described in the balance of this report.

SECTION VI

THE TERRAIN MATRIX

The terrain matrix is made up of elements (combinations of terrain factors) describing the conditions of the surface and subsurface layers of the terrain that affect the generation and propagation of seismic signals induced by an energy source (a target). It was recognized that a matrix could not be designed that would account for every possible variation in terrain conditions that is known to exist in the world. For this reason, the following guidelines were followed in the development of the terrain matrix.

1. All elements of the matrix should be composites of terrain features that could most likely be found in the real world. The matrix elements selected should represent those conditions that would be likely to occur a significant percentage of the time.
2. The matrix should contain combinations of factors that would result in the "best case" and "worst case" performances, and also a combination of factors that would result in performances for several intermediate cases. Thus, the matrix should span the ranges of values that are possible in the world environment.

These elements simulate both cross-country and paved-road conditions. In the cross-country conditions, various combinations of surface and subsurface terrain factors were selected for use in the generation and propagation of seismic signals to the desired target-sensor ranges.[4-9] Pavement conditions[10-12] were selected for generation

of seismic signals, and propagation of a generated seismic signal was computed for the material adjacent to the pavement (i.e., the foundation material under the pavement and base course). This procedure allowed portrayal of a situation in which signals from a target moving along the edge of a roadway would be detected by sensors placed in the in situ material at some distance from the edge of the roadway. In Table 2 matrix elements 1-52 apply to the cross-country terrain conditions, and matrix elements 53-58 apply to the pavement conditions. (See Appendix A for definitions of the terms used in Table 2.)

The terrain factors that significantly influence the magnitude and frequency content of a generated seismic signal are:

1. Ground surface rigidity (surface spring constant, N/m; and maximum deformation, m).
2. Bulk properties (compression wave velocity, m/sec; shear wave velocity, m/sec;and bulk density, g/cm^3).
3. Depths to interfaces, m.
4. Surface roughness, rms elevation in cm. (Important only when it causes motion in the target mass; used primarily for vehicle targets and not walking-man targets.)

These factors are discussed in the following paragraphs.

As a target moves along the ground surface, the material will deform in a nonlinear manner. The amount of deformation can be estimated from load-deflection (plate-load) tests on the material.[1] The force the target applies to the ground with respect to time is related to these ground deformations and, therefore, affects the magnitude of the seismic signal generated by the target. Ground deformation (spring) constants were estimated for each type of material used in the study. The surface deformation of pavement was assumed to be linear and was therefore computed using the compression and shear wave velocities and layer thicknesses.

The properties of the various soil layers (i.e., compression wave velocity, shear wave velocity, bulk density, and thickness of each layer of material) affect, to a great extent, the coupling and propagation

of the generated seismic signal. These parameters vary directly with the type of material present. Generally, a more rigid material will allow less coupling of the signal to the substratum, but will attenuate the signal to a lesser degree as it is propagated. Conversely, a softer material will couple more of the signal energy, but will attenuate the propagated signal to a greater extent. In general, for a given surface soil condition, the shear wave velocity and depth of the first and second layers are good indicators of substratum rigidity and, therefore, to a large extent control the seismic responses from footsteps at a given location.

SECTION VII

ESTIMATING GATOR MINE PERFORMANCE

Computer models were used to generate seismic signals for footsteps for each element in the terrain matrix: These models were the footstep model[1] and the seismic signal model.[2,3] Details of the procedures used to define the Gator mine performance in terms of probability of detection of a man walking for each of the matrix elements are given in the following paragraphs.

In the actual Gator mine logic circuit, a three-phase process leads toward detonation of the mine as follows: Phase 1 requires the mine to identify the signals as valid footstep signals, Phase 2 requires the mine to classify the footstep sequence as being generated by a walking-man target (a randomized criterion), and Phase 3 requires the mine to apply a range-containment criterion to the signal sequence before detonation. In preparation for this processing, footstep signals that would be evidenced at the geophone terminals of the Gator mine were computed for each element of the terrain matrix such that activation of the mine could be readily studied for both target-to-sensor and CPA ranges.

It was desired to study mine performance for footsteps spaced 0.8 m apart on CPA lines of 2, 3, 4, 5, 10, 15, 20, and 25 m as well as various target-to-sensor ranges. Since many target-to-sensor ranges were nearly the same for individual footsteps on different CPA lines, it was convenient to compute signals for target-to-sensor ranges of 2 to 30 m at 0.2-m increments. Thus, 141 separate footstep signals were generated for each of the 58 terrain matrix elements, giving a total of 8178 unique footstep signals for analysis.

The signals in each 141-footstep sequence (corresponding to one of the 58 terrain matrix elements) were converted to analog signals and recorded on magnetic tape. The tapes were sent to Honeywell, where the signals were injected into the Gator mine logic at the place where

the geophone would normally be attached. A notation was made for each footstep signal that was identified by the logic as a valid footstep (Phase 1 in detonation of the mine). This information was then sent to WES for further analysis, i.e., the randomized footstep classifier criterion (Phase 2 in detonation of the mine) was used to determine the CPA lines on which the identified footsteps were classified as a man walking. The results at this point (i.e.,Phases 1 and 2) gave the Gator mine performance in terms of identification and classification and were used to compute detection results in terms of target-to-sensor range and CPA range for each matrix element so that the results could be compared with Gator mine performance data previously collected by the Honeywell and Eglin AFB personnel. The range-containment criterion (Phase 3) was not applied in this study since it would not provide any additional insight into the immediate problem of terrain constraints on the mine's seismic logic performance.

TARGET-TO-SENSOR RANGE

The probability-of-detection (correct identification and classification) results for each element in the terrain matrix are shown in Table 3. The probability-of-detection values (the last column in Table 3) give the number of trails in percent in which the Gator mine logic circuits correctly identified the computer-predicted signals as footsteps and made a correct classification for a walking-man target walking with a 0.8-m stride nearly radially to the mine (i.e. on a 2-m CPA line). This simulates a scenario in which a walking man initiates travel beyond the threshold of detection for the mine and walks on a straight path which takes him within 2 m of the mine at the closest point of approach. Table 3 shows that there was no activation of the Gator mine in 32 of the 58 terrain elements. Signals from six of these matrix elements were identified as footsteps but were not classified as being generated by a walking-man target; these matrix elements were 7, 10, 16, 23, 27, and 42. Also, there is a tendency for the logic to be

activated for all trials for a given matrix element (see the 100-percent probabilities in the last column of Table 3) if an activation occurs on any trial. Exceptions to this trend can be seen for matrix elements 14, 30, and 45 where the probability of detection was 95, 58, and 85, respectively.

Although the probability of detection for a given matrix element is a good indicator of how the logic will perform in that terrain element, it does not tell the complete story. Where the logic activates in relation to the target is of prime importance in regard to determining the lethality of the mine. For this reason it is customary to study the distribution of target-to-sensor ranges for those mines that are activated. These data are presented in Table 3 under the heading Normalized Probability of Detection, percent. For example, consider the data presented for matrix element 14. For all trials studied, 95 percent of them resulted in an activation of the logic; 18 percent of the 95 percent were activated at ranges varying from 5 to 10 m, whereas 82 percent of the 95 percent were activated at ranges varying from 0 to 5 m. For a further example, consider the data for matrix element 1. All trials resulted in an activation and all activations occurred in the 15- to 20-m range. This does not imply that the logic would not activate in the 0- to 15-m range; it would, but information is not of interest because once the logic is activated and the range-containment criterion is satisfied, the mine detonates. If the intruder's footsteps were continued and the sensor logic reset, detection would probably continue through zero ranges. From the data (Normalized Probability of Detection, percent) in the center of Table 3, it can be seen that for the majority of terrain elements that resulted in logic activations most occurred in ranges from 0 to 10 m.

The data shown in Table 3 and discussed above should be compared with discretion with field-measured probability-of-detonation results from studies performed in the past for the Gator mine program, since the range-containment feature was not used in the computations as noted above. If the range-containment feature had been used, it is likely that activations would have occurred at slightly shorter ranges.

CPA RANGE

It is also customary to present mine activation data in terms of CPA range because it conveniently provides insight into how mine spacing affects mine field penetrability. To arrive at CPA data, the valid footsteps from each 141-footstep sequence (for each matrix element) were arranged into CPA lines at 2, 3, 4, 5, 10, 20, and 25 m by identified footstep signals from the 141-footstep sequence at the proper range for a 0.8-m stride along each CPA line. Figures 2-27 show percent detection versus CPA distance for the signals from the 26 matrix elements that were correctly identified as footsteps and classified as generated from a walking-man target by the Gator mine logic. For example, Figure 2 (matrix element 1) shows that at CPA distances up to 20 m, there is a 100 percent chance the mine will be activated and at CPA distances of 35 m and beyond there is zero chance of mine activation. (It should be noted that target-to-sensor ranges cannot be derived from the data shown in Figure 2, i.e., activation can occur anywhere on the various CPA lines.)

SECTION VIII

EVALUATION OF THE GATOR MINE LOGIC

From the previous discussion it is apparent that the present Gator AP mine is inoperable in a variety of terrain conditions. Fortunately, the terrain factors that affect the performance of the Gator mine have been defined in quantitative terms, thereby providing a means for studying Gator mine performance as a function of critical terrain factors. For example, previous studies (reference 1) at WES have shown that the shear wave velocity of the surface and subsurface soils strongly controls the generation and propagation of seismic energy from footsteps. If the Gator mine logic could be shown to operate over the range of shear wave velocities found in nature, it could be assumed that it would probably work within a large variety of field conditions. Figure 28 displays the shear velocities for the various terrain matrix elements, i.e., top-layer-material shear wave velocity versus foundation-material shear wave velocity, along with the general descriptions of the materials commonly found with the various shear wave velocities (a more complete description of each element is given in Table 2). Each of the crosses in Figure 28 represents several elements in which the layer thicknesses are different (e.g., top layer is 0.25, 1.5, or 4.0 m thick). The values of shear wave velocities shown are presented to span the range of values found in nature (excluding hard, competent rock); therefore, note that the top-layer-material shear wave velocity ranges to about 1500 m/sec. It is possible to find top and foundation layers that exhibit the full range shown; however, velocities in surface layers greater than about 600 m/sec are relatively uncommon.

It is emphasized that shear wave space (Figure 28) is only one way of displaying the factor data making up the elements of the terrain matrix. However, as stated earlier, the shear wave velocity of a material has been shown to be a very sensitive indicator of the seismic responses from footsteps. For this reason a preliminary evaluation of

the present design of the Gator mine logic was made in terms of shear wave space. The results of this analysis are described in the following paragraphs.

To illustrate how the Gator mine logic performed in shear wave space, certain data presented in Table 2 and Figures 2-27 were extrapolated and plotted in shear wave space (Figures 29-31). Specifically, for each matrix element containing a shallow or deep top layer (i.e., d = 0.25 or 4 m, respectively), the probability of detection at the 5-, 10-, and 15-CPA lines were determined from Figures 2-27. If a probability of activation occurred for a given matrix element, its position in shear wave space (see Table 2 for shear wave velocities for each matrix element) was plotted in Figures 29, 30, and 31 for CPA lines of 5, 10, and 15 m, respectively. Thus, the solid lines approximate the shear wave space in which activation would occur for the various CPA distances. The detection envelope for each of these figures was drawn based on the pattern developed on all CPA lines and not solely on the data from one line. It should be noted that the Gator mine logic must be able to work throughout the total shear wave space if it is to work worldwide. However, because data are not available to specify the relative worldwide occurrence of various regions of shear wave space, the absolute consequence (in terms of the percentage of the world's land mass in which the Gator logic will not work) of a shear-wave-space area not being enveloped cannot be determined. Gator mine logic performance in terms of shear wave space is discussed in the following paragraphs.

In each case for shallow top-layer materials, detection took place over relatively narrow ranges of foundation-material shear wave velocity and correspondingly wide ranges of top-layer velocity. For deep top-layer materials, the reverse is true; detection took place over relatively narrow ranges of top-layer shear wave velocity and wide ranges of foundation-material velocity. This would suggest, at least for the 5- and 10-m CPA lines, that the Gator mine logic is relatively insensitive to the soil properties above 0.25 m (the shallow top-layer thickness) or below 4 m (the deep top-layer thickness). For detection

on the 15-m CPA line, the envelopes are similar to those shown on the 5- and 10-m CPA lines, but occupy smaller areas. The 15-m CPA lines still show detection when the top-layer shear wave velocities are between 60 and 460 m/sec, but only for foundation-material shear wave velocities of approximately 100 to 250 m/sec and 200 to 450 m/sec for shallow and deep top-layer materials, respectively. Overlap of the shallow and deep top-layer envelopes occurs for the 5- and 10-m CPA lines, but not for the 15-m CPA lines. This overlap is in that part of shear wave space wherein the top-layer and foundation materials have approximately the same shear wave velocity, i.e., where there is relatively little contrast between the two materials.

Figures 32-34 show CPA contour lines at 2, 5, 10, 15, and 20 m for man-walking detection for shallow (0.25-m depth), intermediate (1.5-m depth), and deep (4.0-m depth) top-layer materials, respectively, over a foundation. As before, these contour lines are mapped in shear wave space. Probability-of-detection values for shallow and deep top-layer materials were zero on 25-m CPA lines (see Figures 2-27); therefore, the 20-m CPA line contour (Figures 32 and 34) is the final one drawn. On the intermediate (1.5-m) top-layer material, detection stops with the 15-m CPA line, so the 10-m CPA contour is the final one drawn (Figure 33). These curves also indicate that a rapid fall off in detection occurs (i.e., the enclosed areas get much smaller) for CPA lines greater than 10 m for all layer thicknesses.

For the Gator mine to be most effective under actual battlefield conditions, it must be insensitive to, or independent of, layer conditions. Figure 35 shows the areas in shear wave space in which minimum performance can be expected independent of layer thickness. The largest area on this map is that shown for footstep identification only (i.e., classification of the footstep signals is not made for a walking-man target) on a CPA line of 2 m. The succeeding contour lines shown are those for man-walking detection (footstep identification and classification) at 2, 5, and 10 m in decreasing size of enclosed area. Note

that operation independent of layer thickness took place only in a well-defined area of the shear wave space, i.e., between velocities of approximately 100 and 500 m/sec. As the CPA distance becomes larger, the contrast between the top layer and the foundation must be smaller for detection to take place. At the highest CPA distance plotted (10 m), the area displayed is centered over the areas representing no layering at all (the top-layer material has approximately the same shear wave velocity as the foundation material).

SECTION IX

SUMMARY

A new procedure has been demonstrated for defining operational problems of seismic devices. This procedure is based on modeling seismic signals from footsteps and mathematically converting these signals so that they appear as the electrical signals of the Gator mine geophone. Signals thus generated were processed by the actual Gator mine logic and the results tabulated. The procedures were validated by comparing predicted and measured results at four field sites.

A similar procedure was used for signals generated for elements of a terrain matrix. The matrix spanned ranges of properties that could be found in worldwide conditions. The results of analysis of the signals generated for the terrain matrix and processed through the Gator mine showed:

1. The present processing circuits for the Gator AP mine would not detect a man walking from all the terrain elements generated for this study and, therefore, the present design will not operate in all worldwide environments.
2. The maximum CPA line that could be processed for a detection of footstep signals was greater than 20 m, but less than 25 m. A rapid fall off in detection for CPA lines greater than 10 m was noted.
3. Under the restriction of operation in terrain conditions independent of top-layer thickness, the maximum CPA line that could be processed for a detection of footstep signals was greater than 10 m, but less than 15 m. However, at the 10-m CPA line, operation was restricted to relatively small areas of shear wave space where the top layer and foundation had little contrast in properties.

4. The Gator AP mine was most sensitive to ground-layer properties between depths of 0.25 and 4 m.
5. The best performance of the Gator mine was found to be in media with shear wave velocities between 100 and 500 m/second. This represents the portion of shear wave space wherein most of the surface soils are found.

It is recommended that:

1. The information contained in this report be expanded and used to define the limits of expected and desired performance for advanced designs of the AP mine of the Gator mine system. As a first step in this direction, a study should be initiated to define which parts of the world are represented by the various terrain matrix positions and if any significant part of the world is not represented in the matrix.
2. Field test sites for the Gator mine should be real-world examples of the terrain matrix positions (Figure 28) and should span the same areal and positional breadth found in nature (identified in 1, above). This will permit a more accurate evaluation of seismic mine systems under worldwide conditions.
3. Design specifications be generated from the results of this study so that sensor designers can make realistic tradeoffs between detection distance and worldwide operation. Such specifications should be based on both site properties and actual characteristics of predicted wave forms for signals traveling through surface terrain material.
4. Information similar to that presented in this report be assembled for the final design of the Gator mine system and cataloged for possible use in Gator mine deployment

manuals. Such cataloged performance tables should be developed in terms of easily identifiable interpretation keys or remote sensing techniques to supplement existing data banks of seismic information.

5. The range-containment criterion should be applied to the computed signals in any future study so that the results derived in the computer studies can be compared directly with field-measured results .

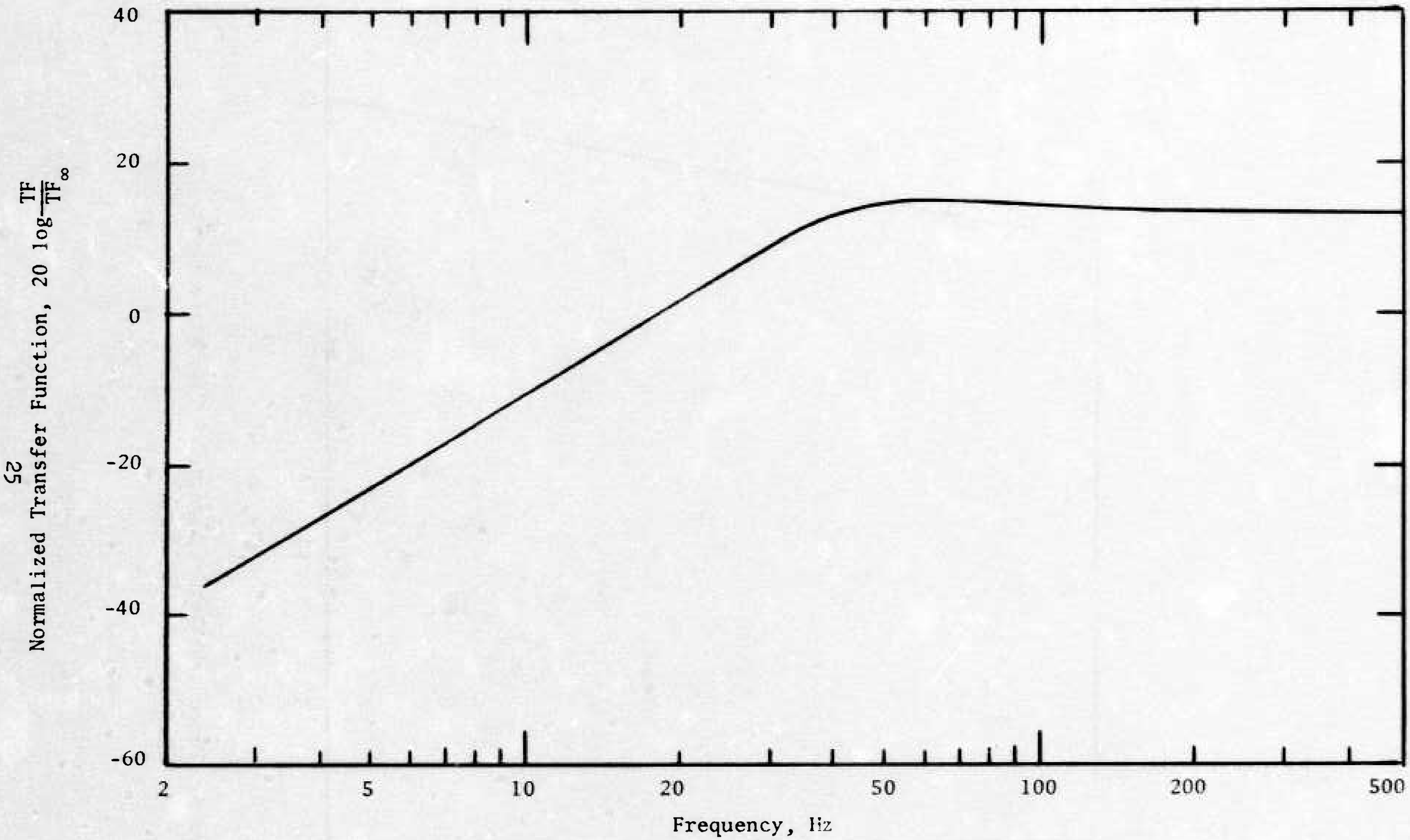

Figure 1. Gator Mine Seismic Transfer Function Magnitude Normalized by the Gator Mine Geophone Sensitivity

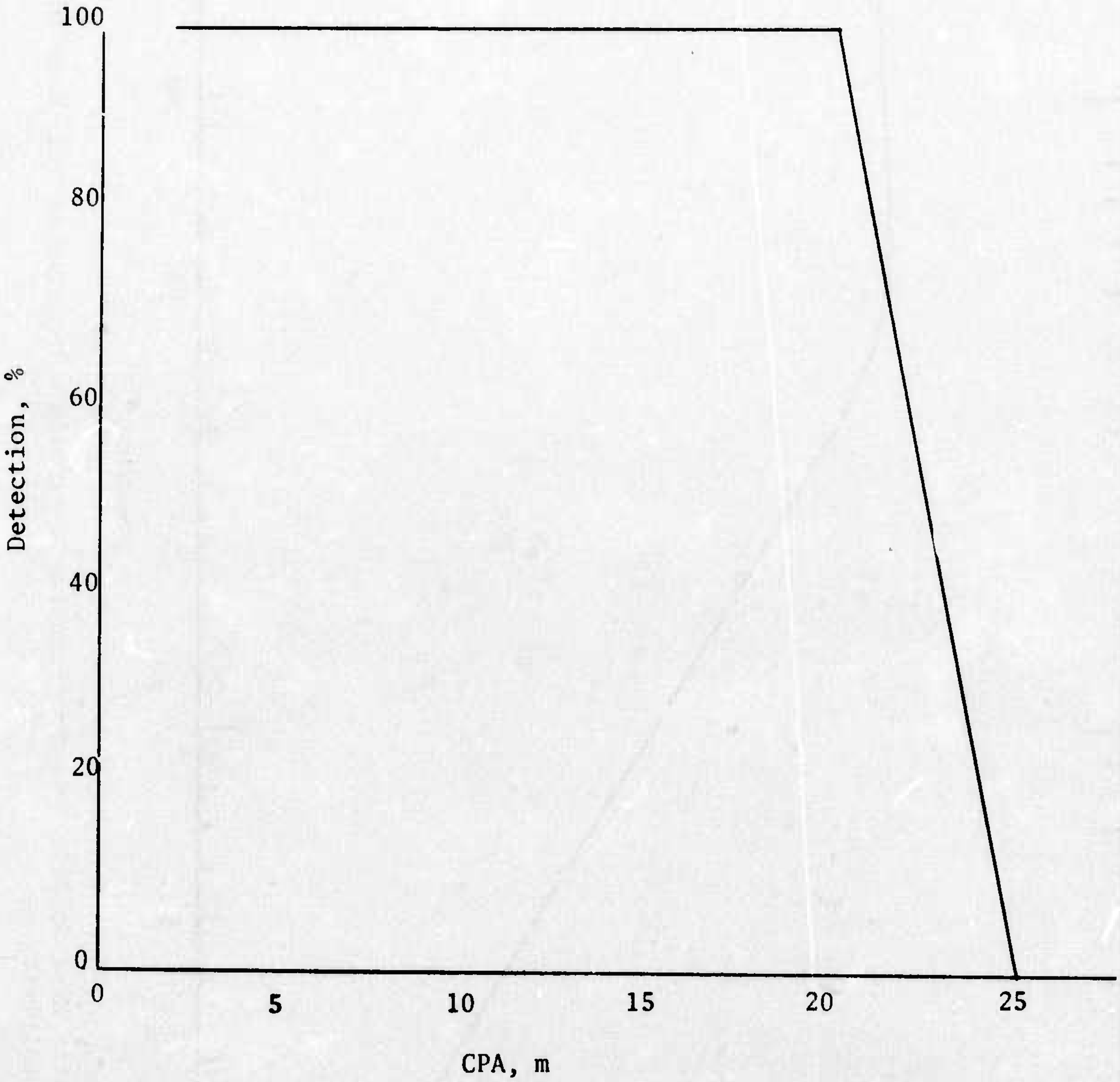

Figure 2. Percent Detection Versus CPA for Matrix Element 1

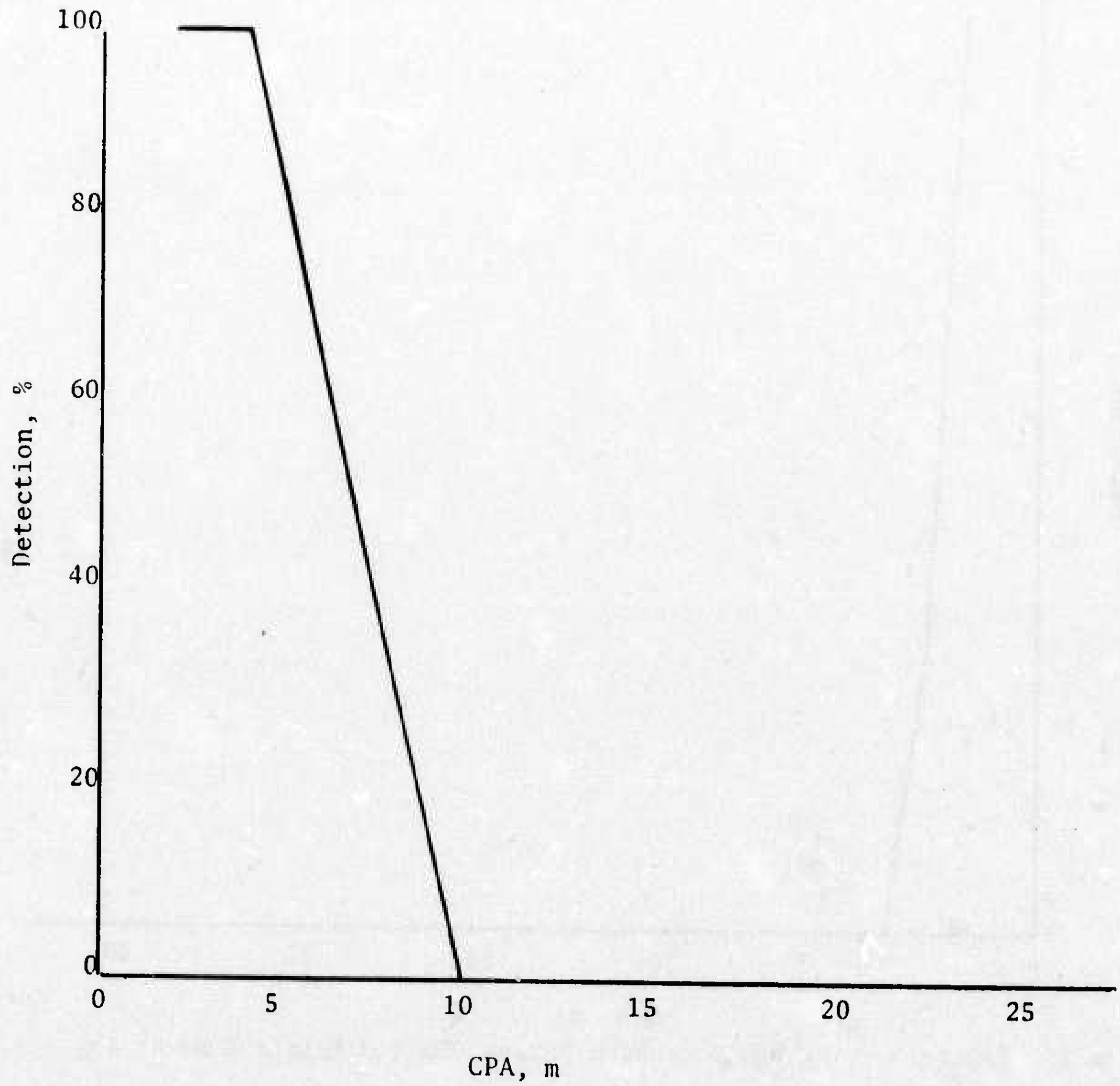

Figure 3. Percent Detection Versus CPA for Matrix Element 4

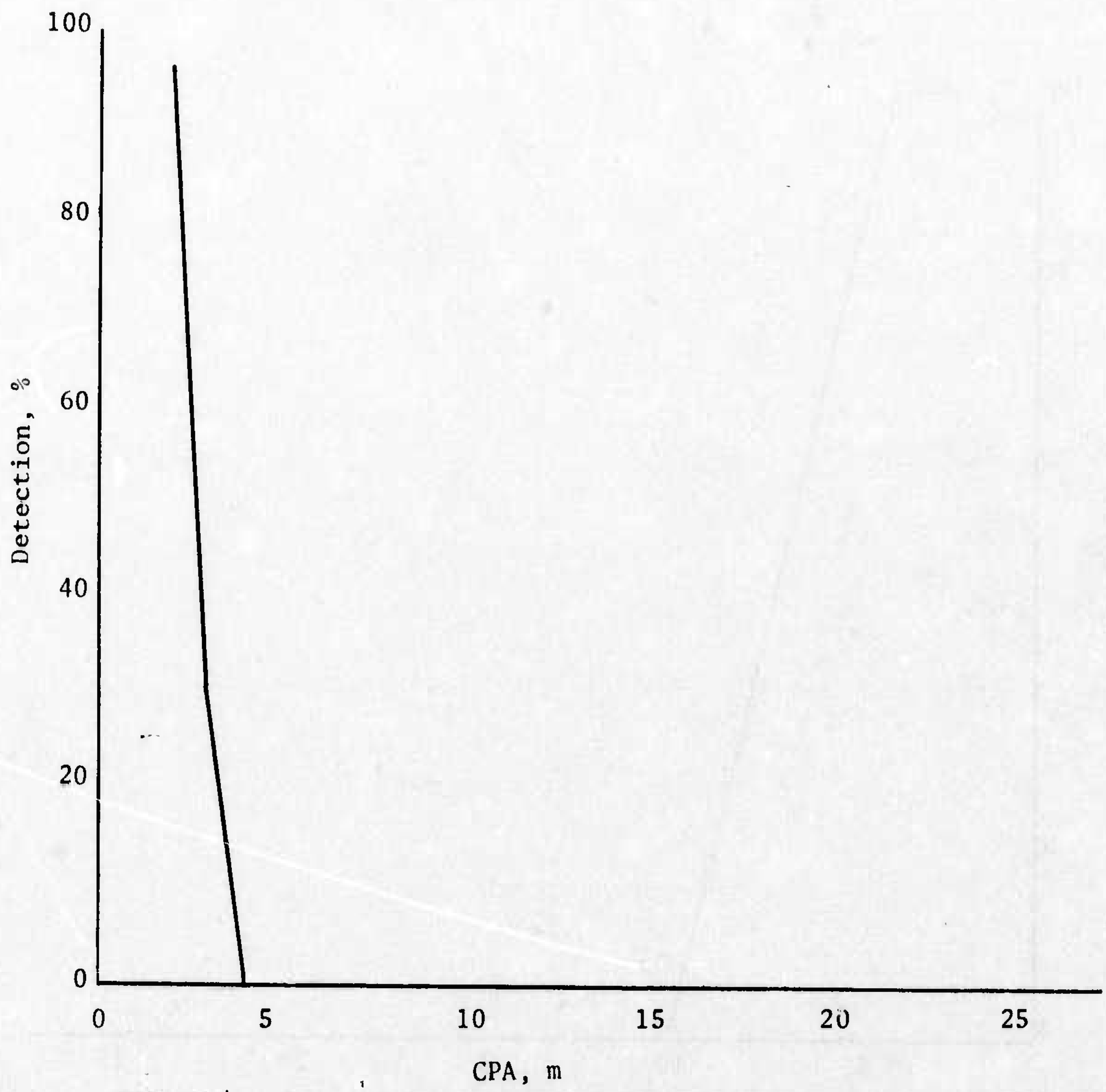

Figure 4. Percent Detection Versus CPA for Matrix Element 14

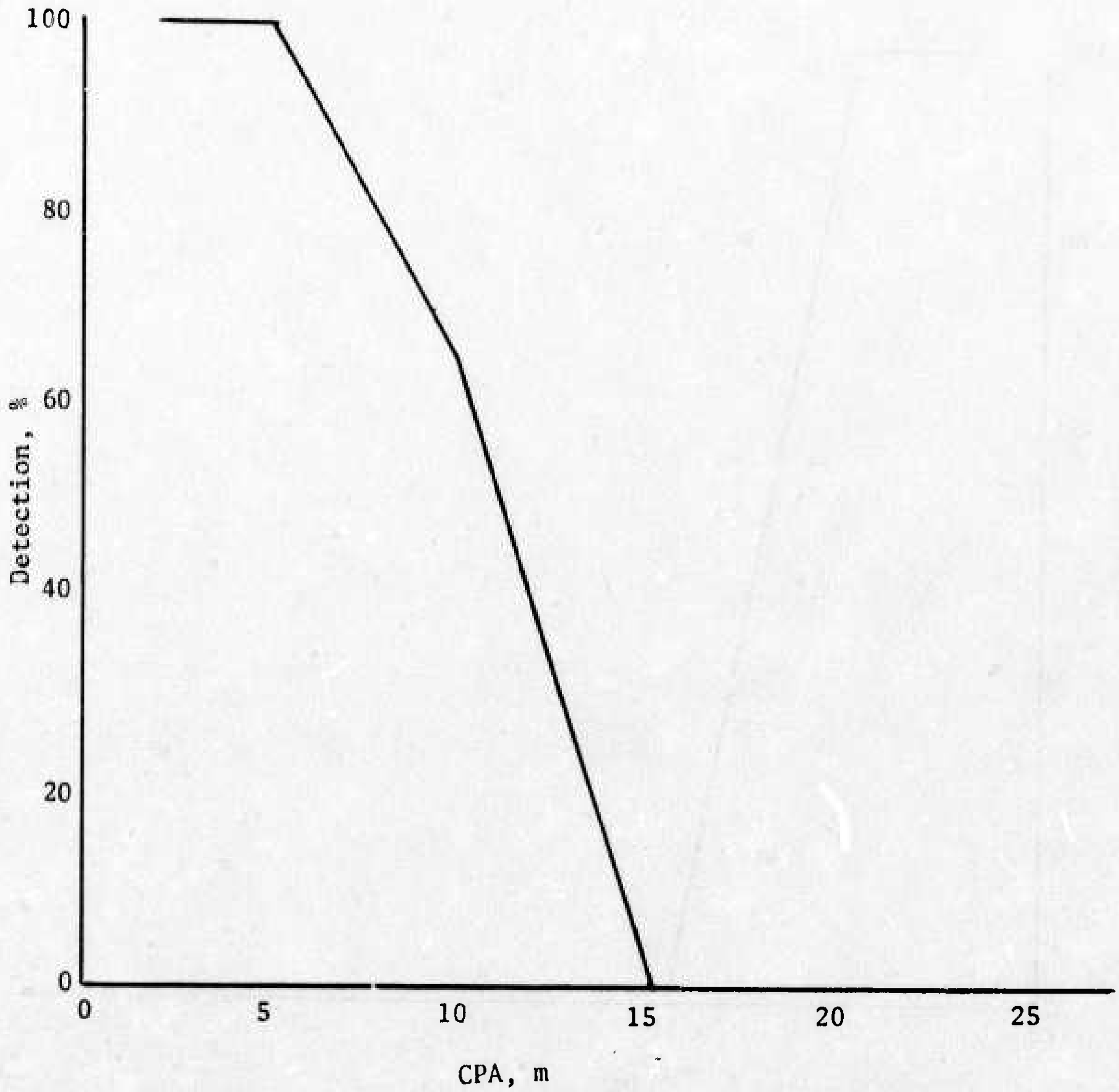

Figure 5. Percent Detection Versus CPA for Matrix Element 19

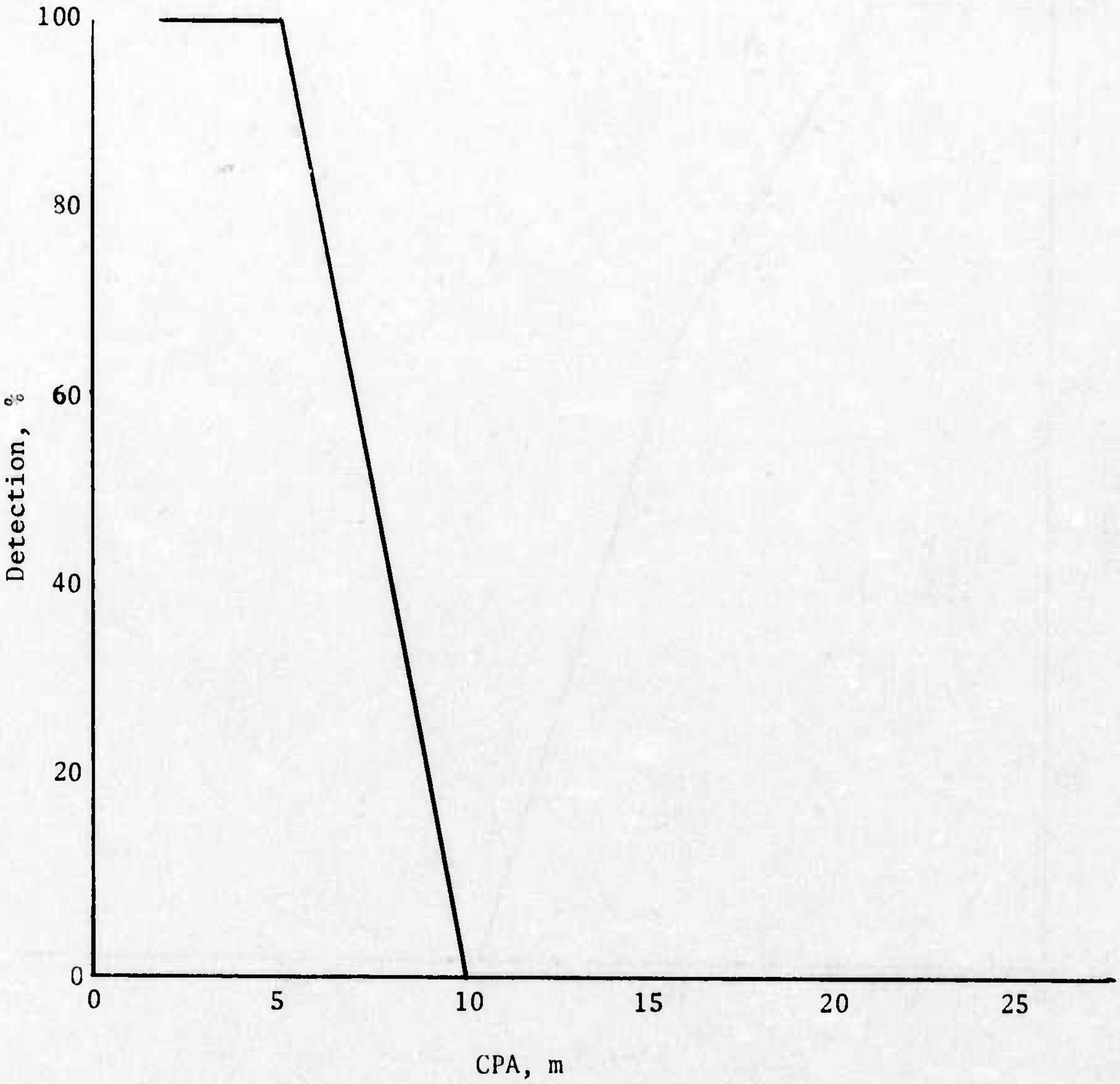

Figure 6. Percent Detection Versus CPA for Matrix Element 20

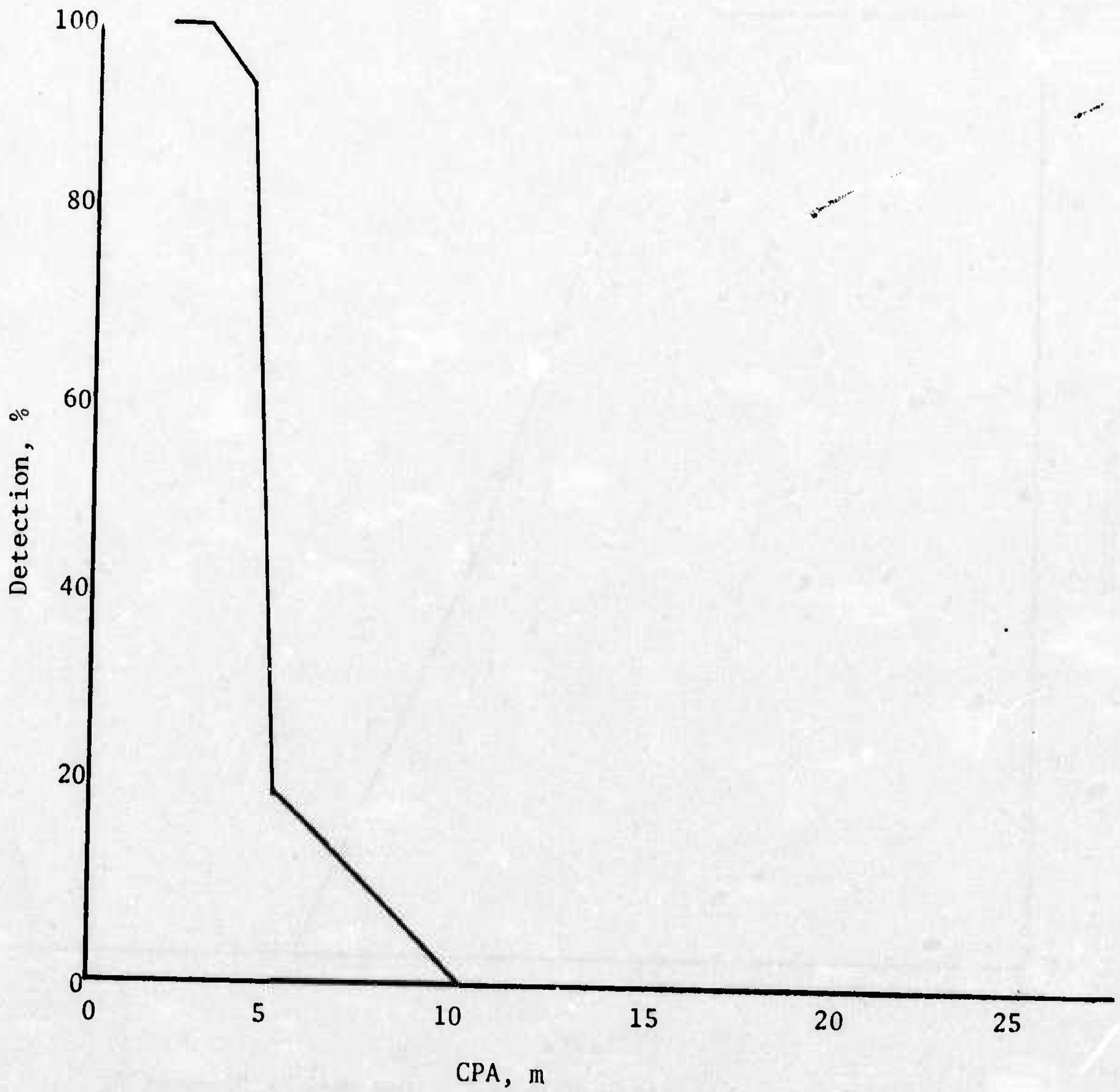

Figure 7. Percent Detection Versus CPA for Matrix Element 21

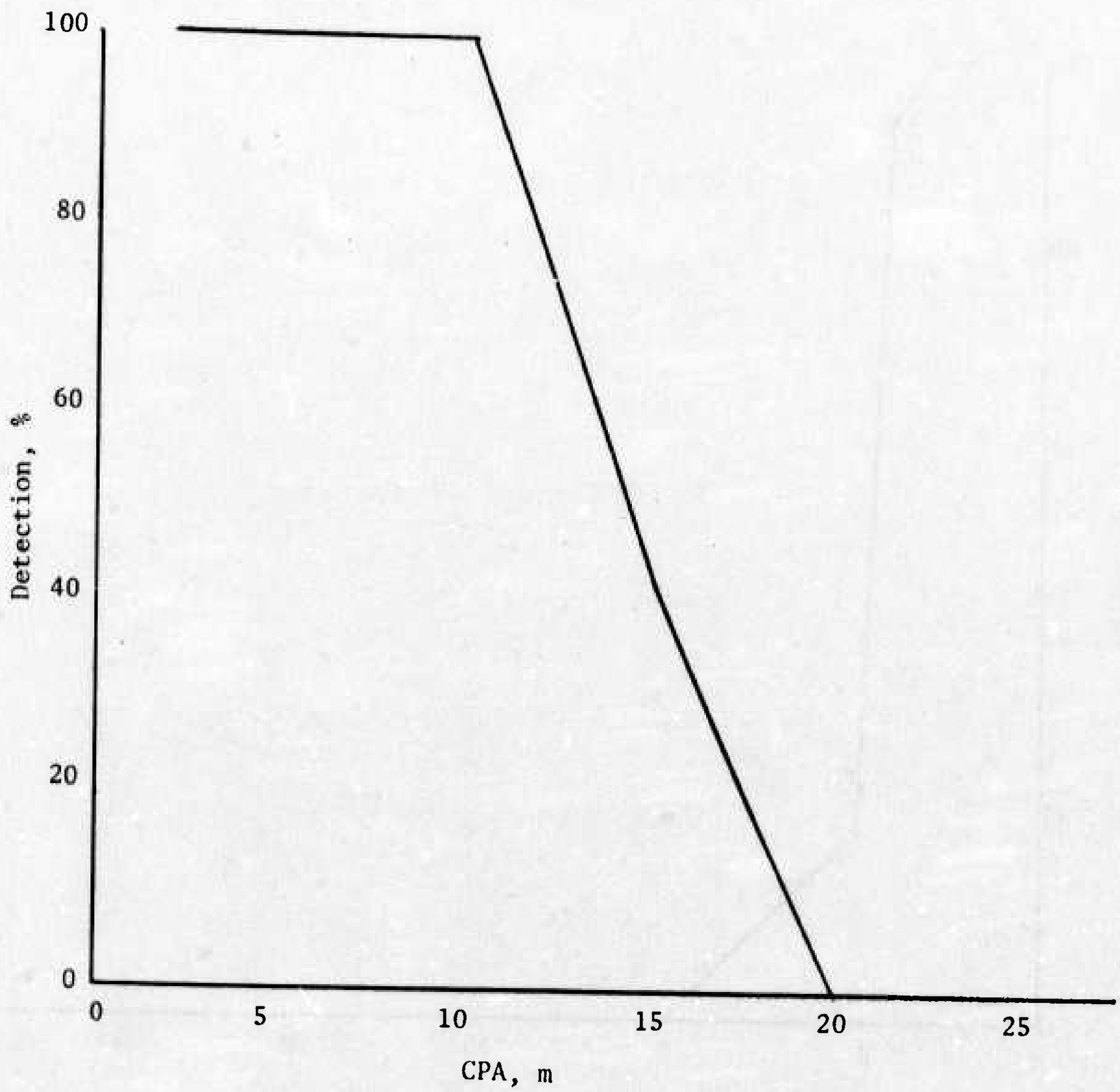

Figure 8. Percent Detection Versus CPA for Matrix Element 22

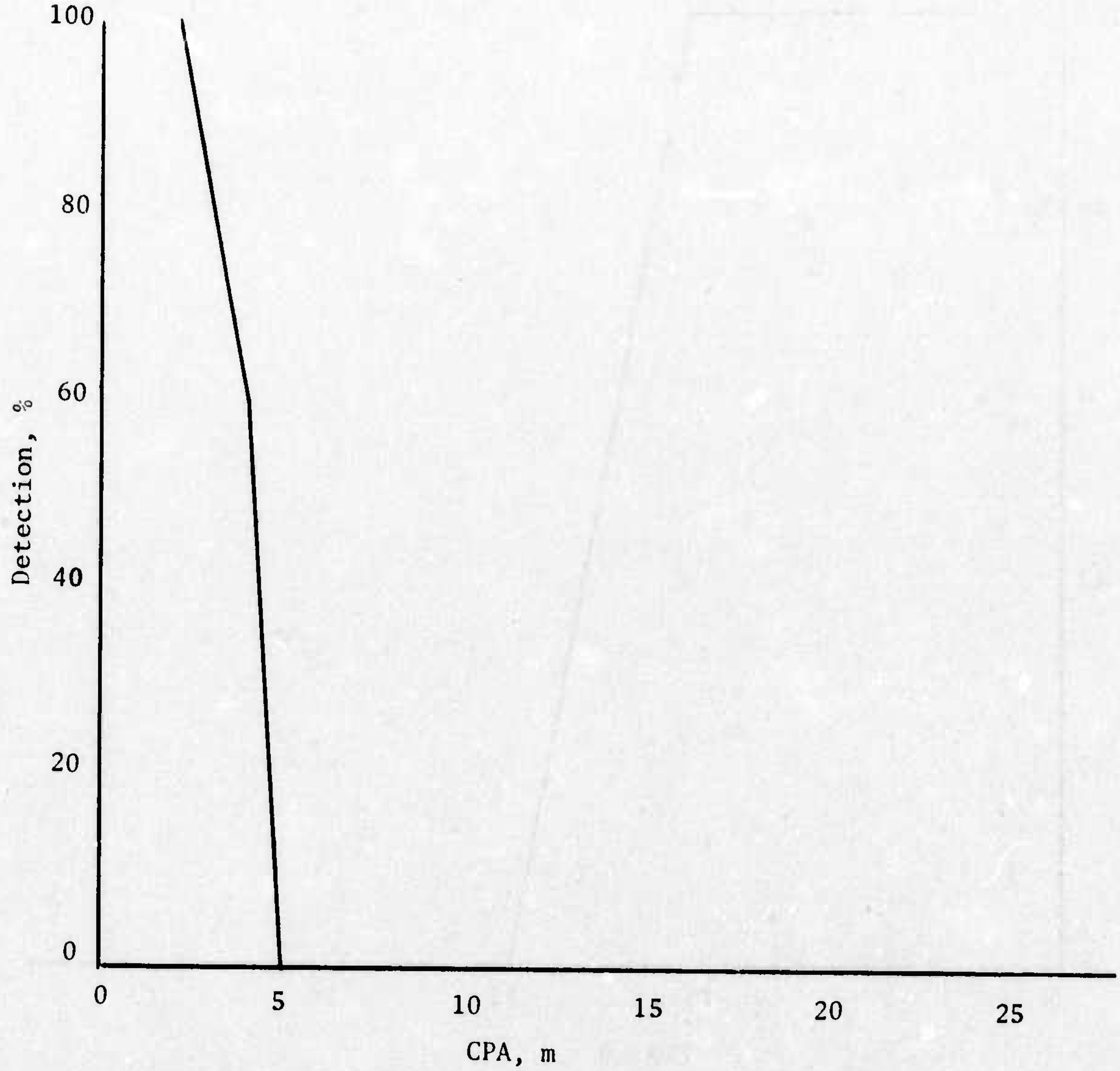

Figure 9. Percent Detection Versus CPA for Matrix Element 24

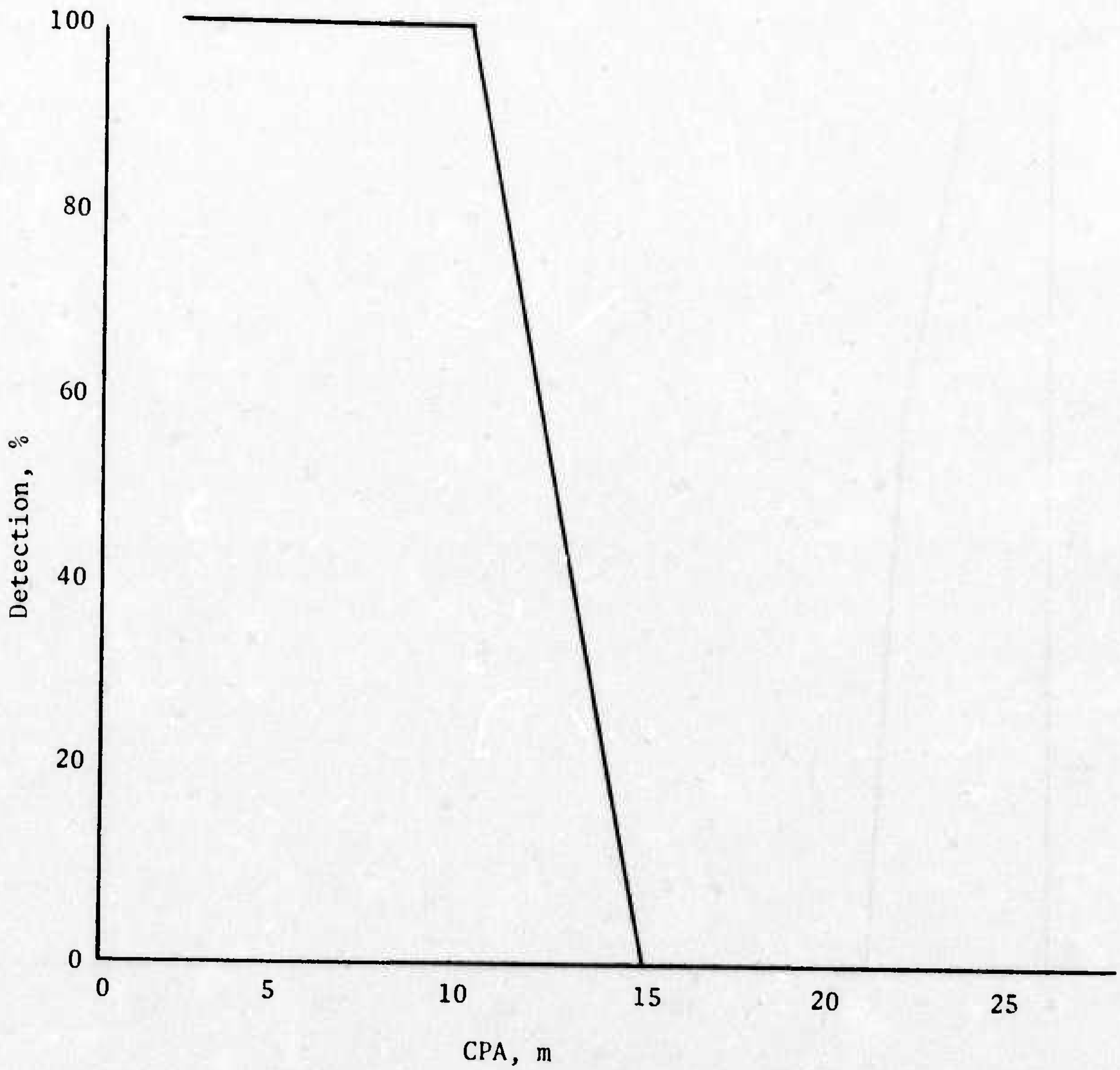

Figure 10. Percent Detection Versus CPA for Matrix Element 25

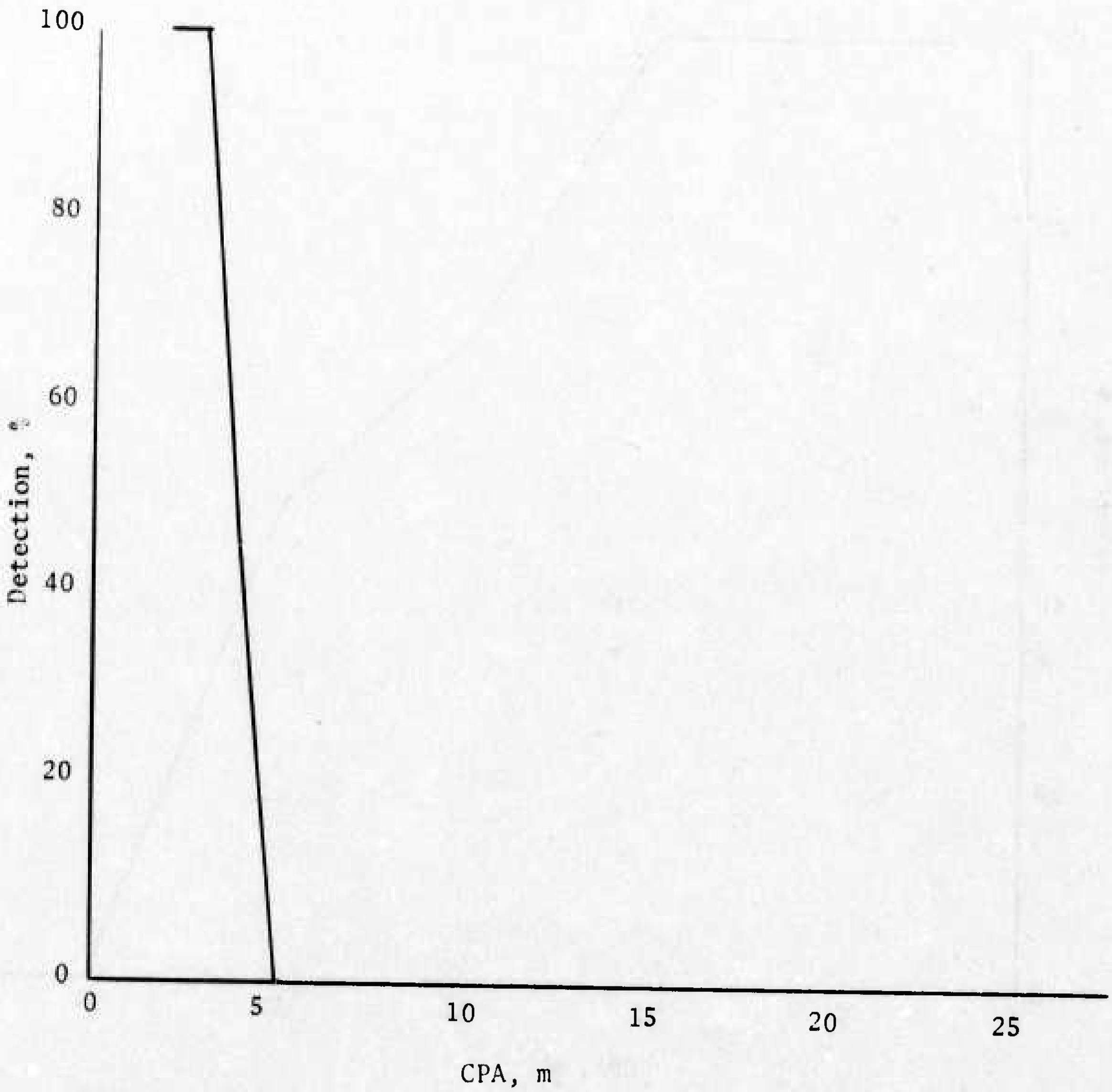

Figure 11. Percent Detection Versus CPA for Matrix Element 26

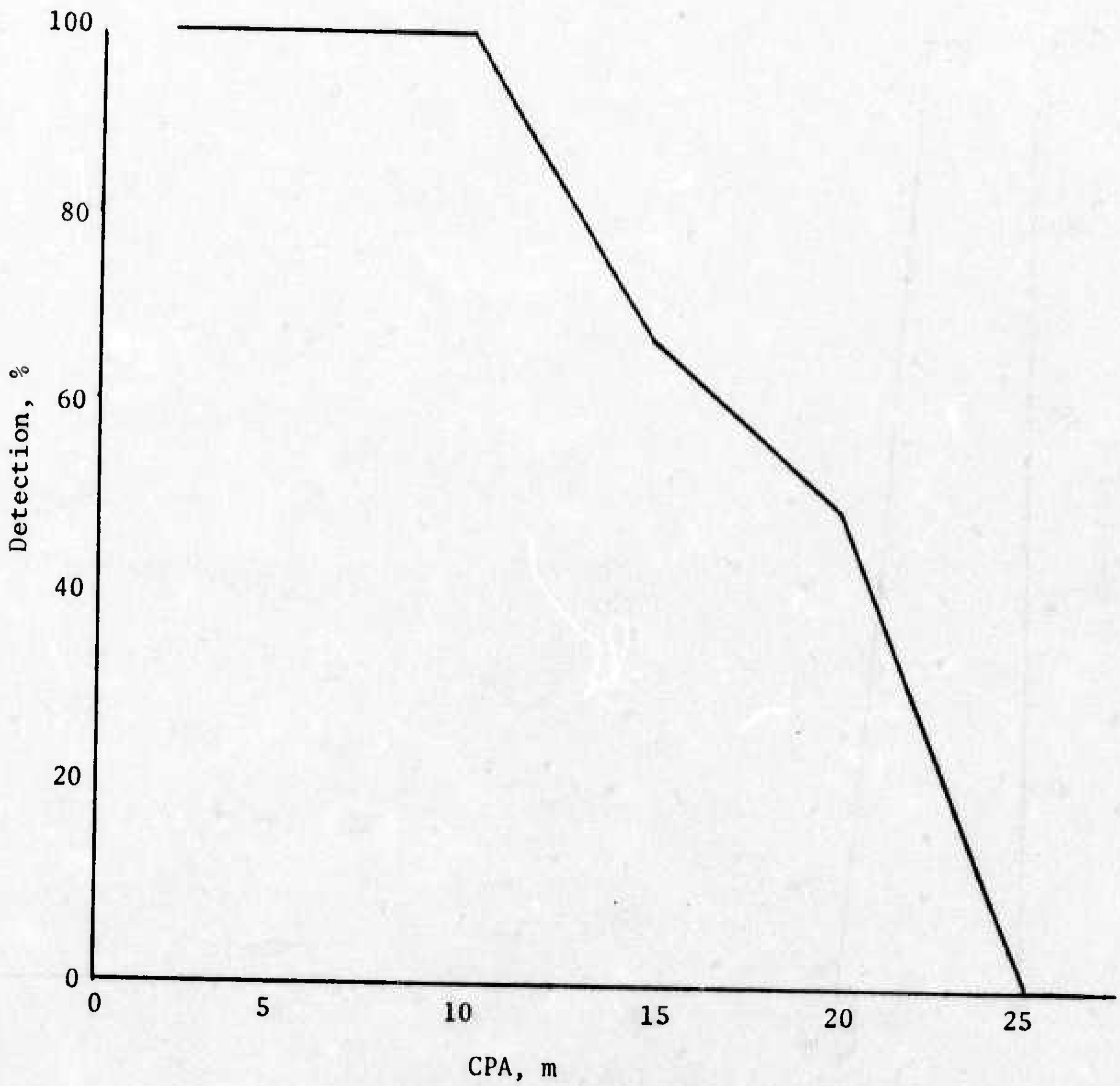

Figure 12. Percent Detection Versus CPA for Matrix Element 28

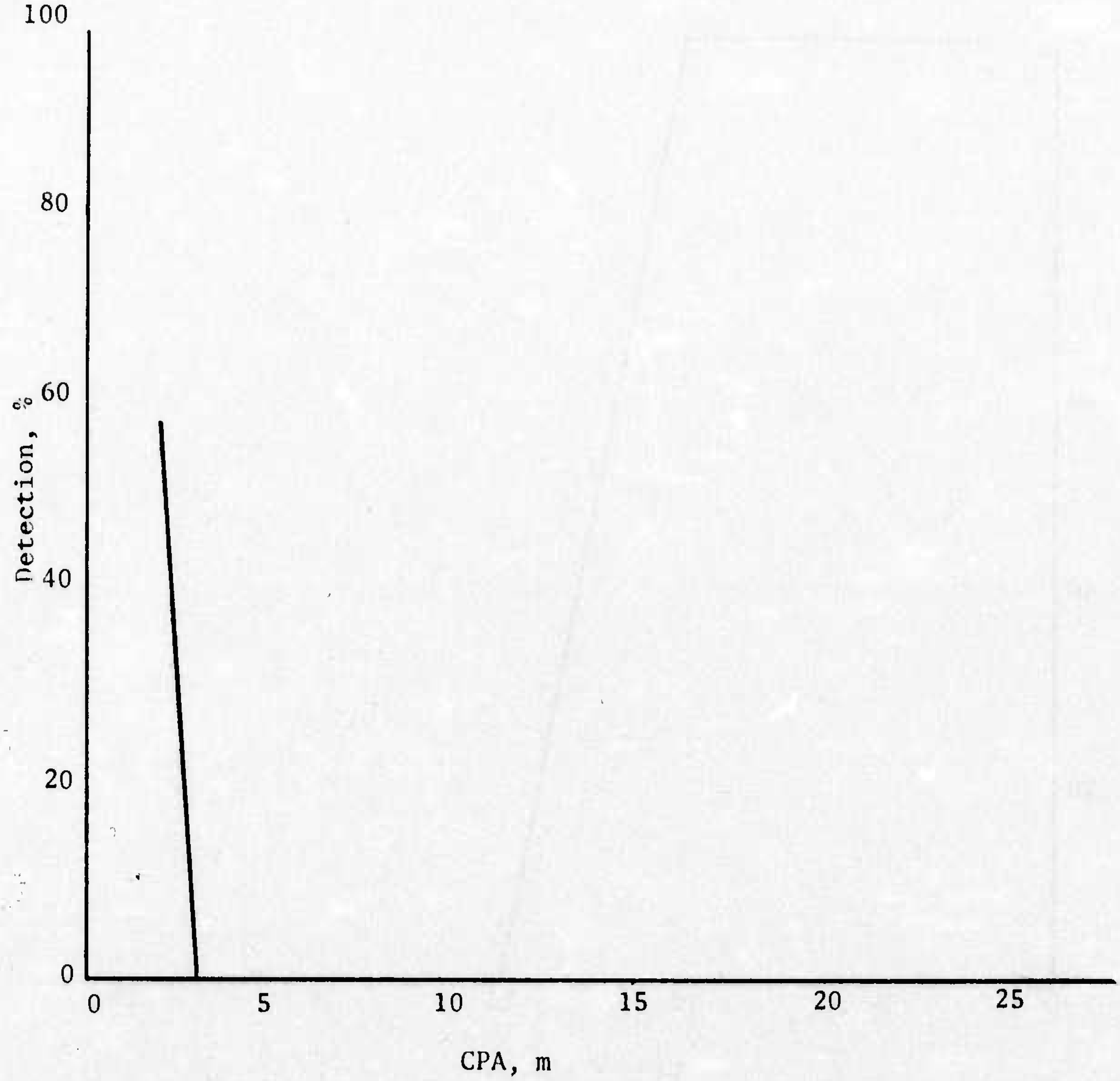

Figure 13. Percent Detection Versus CPA for Matrix Element 30

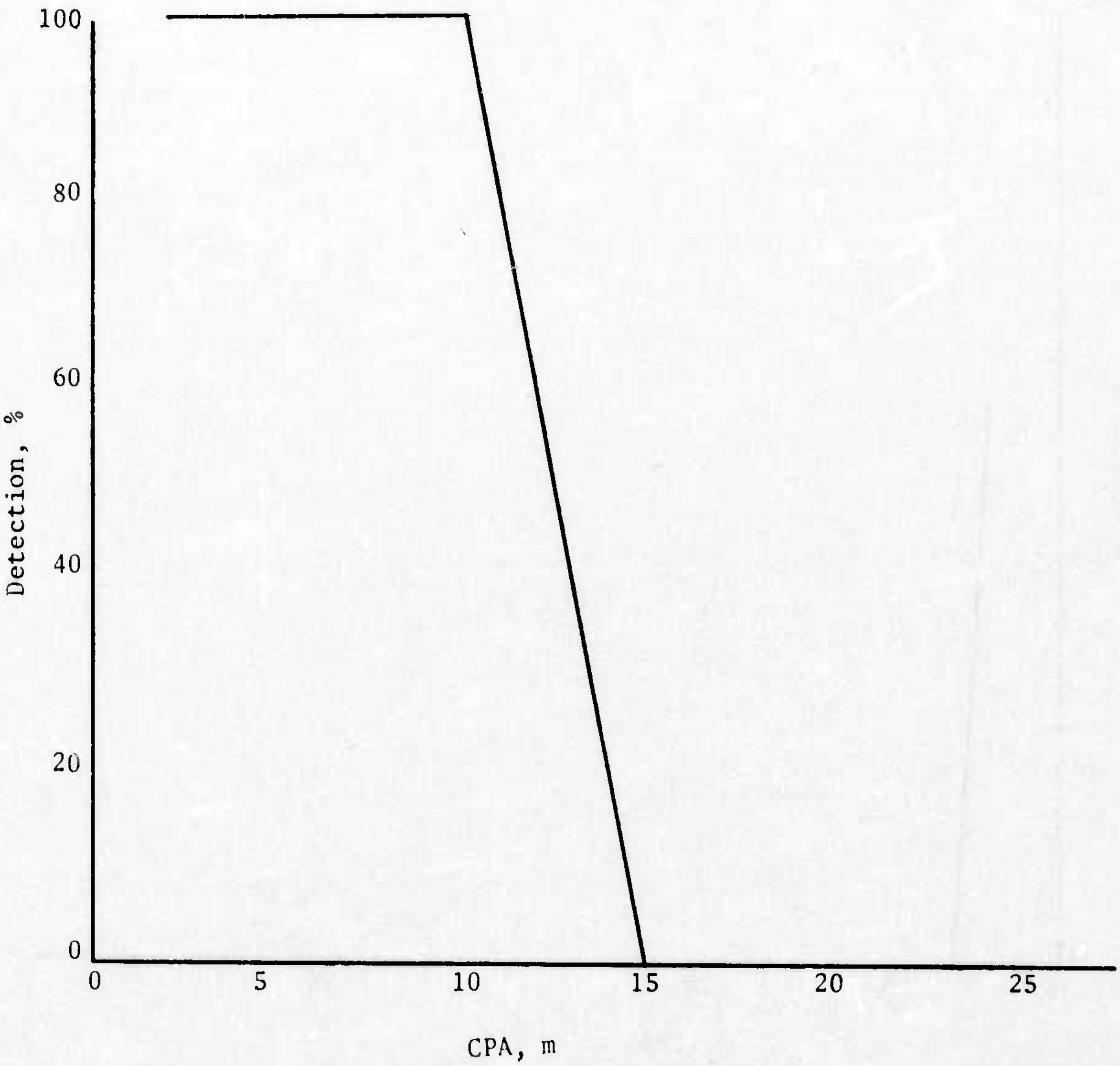

Figure 14. Percent Detection Versus CPA for Matrix Element 31

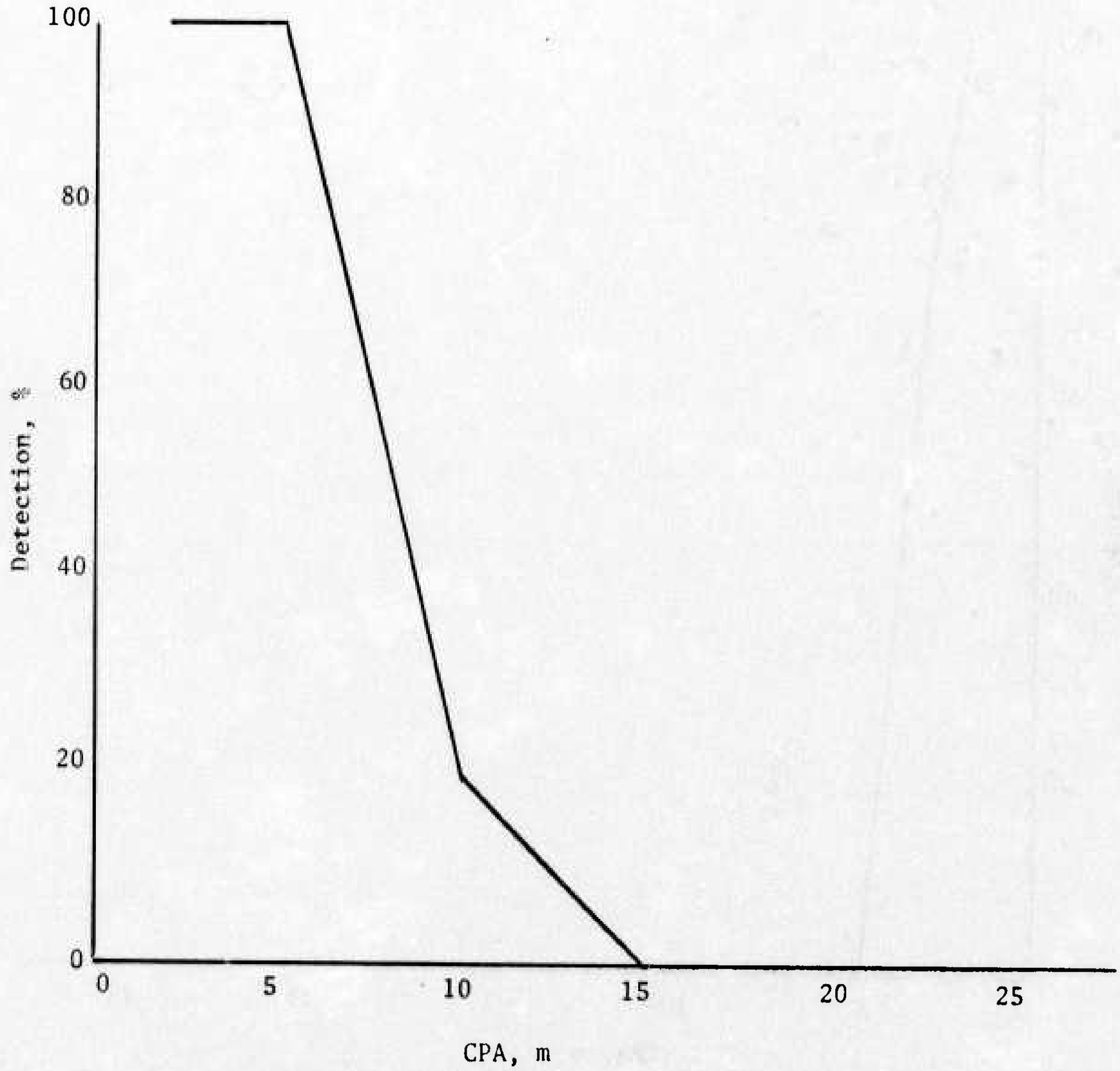

Figure 15. Percent Detection Versus CPA for Matrix Element 32

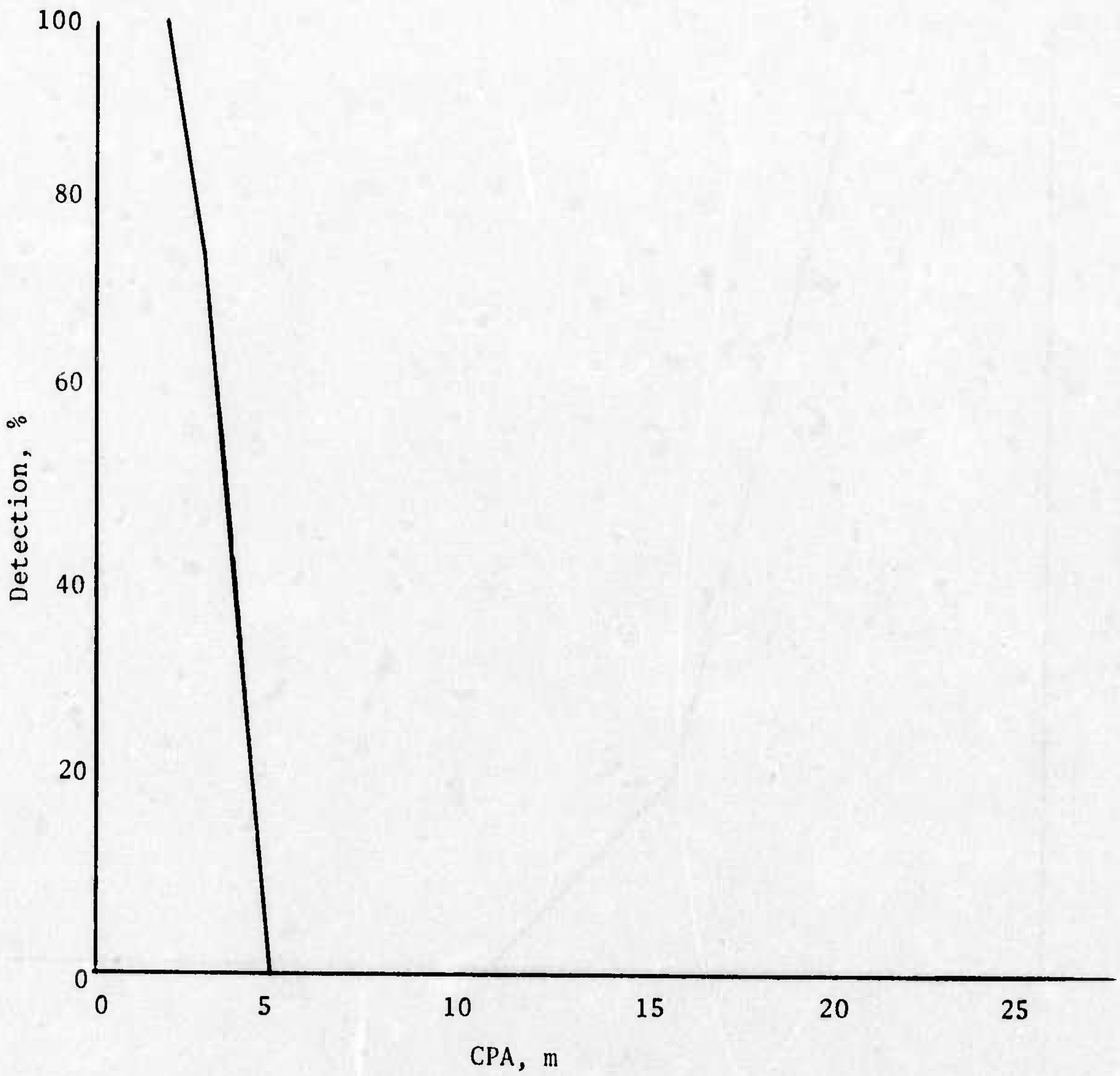

Figure 16. Percent Detection Versus CPA for Matrix Element 33

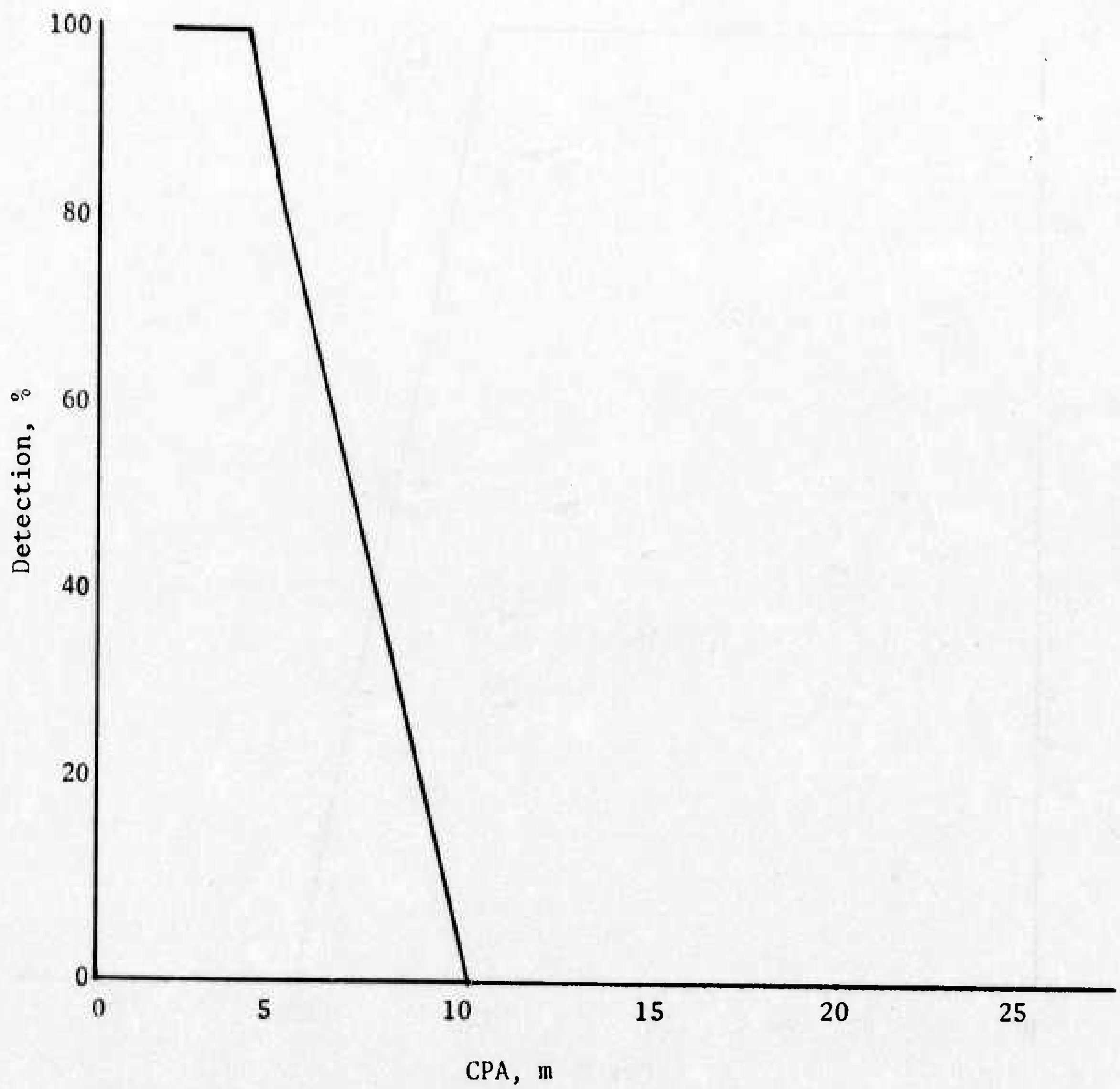

Figure 17. Percent Detection Versus CPA for Matrix Element 34

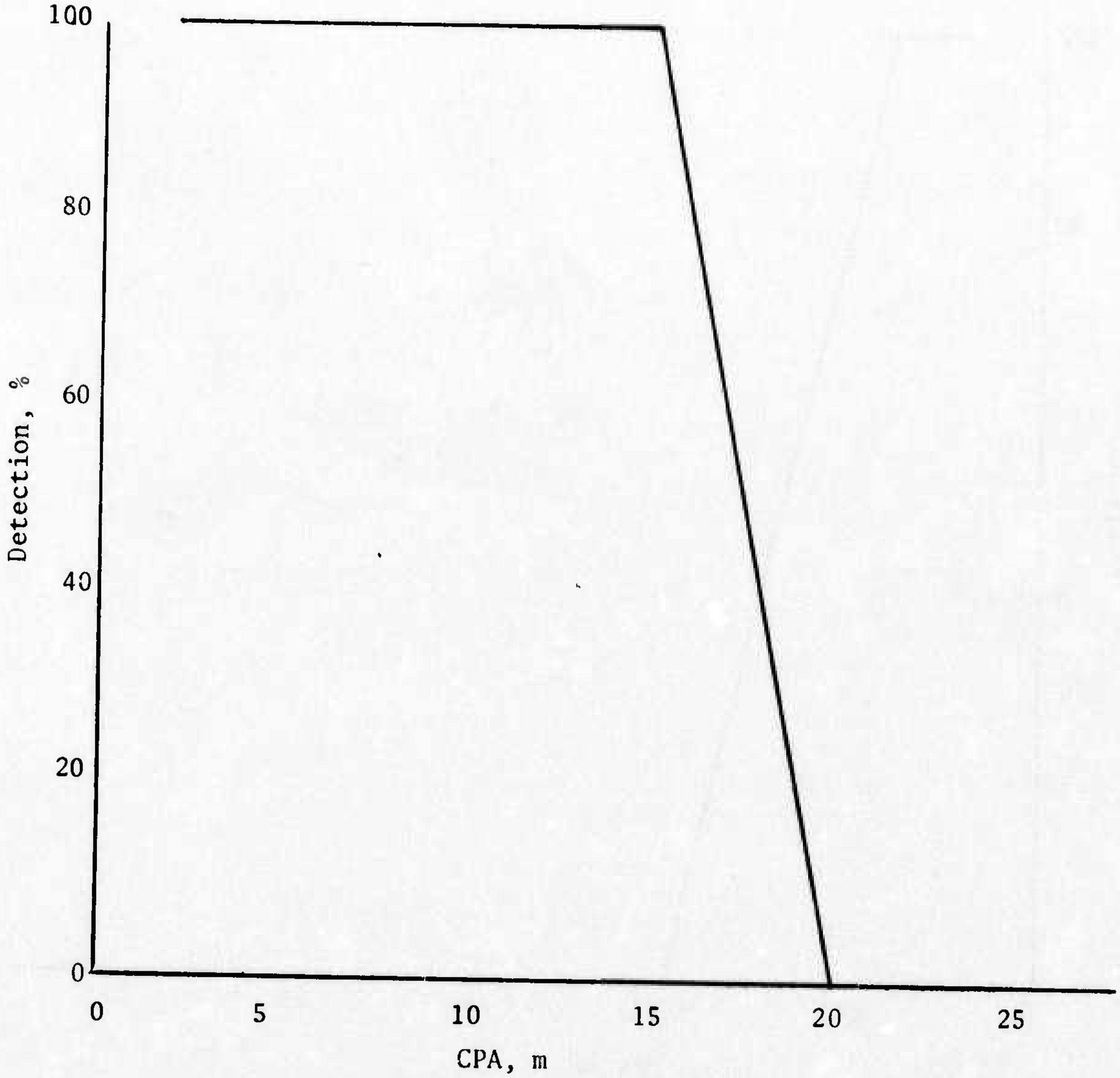

Figure 18. Percent Detection Versus CPA for Matrix Element 35

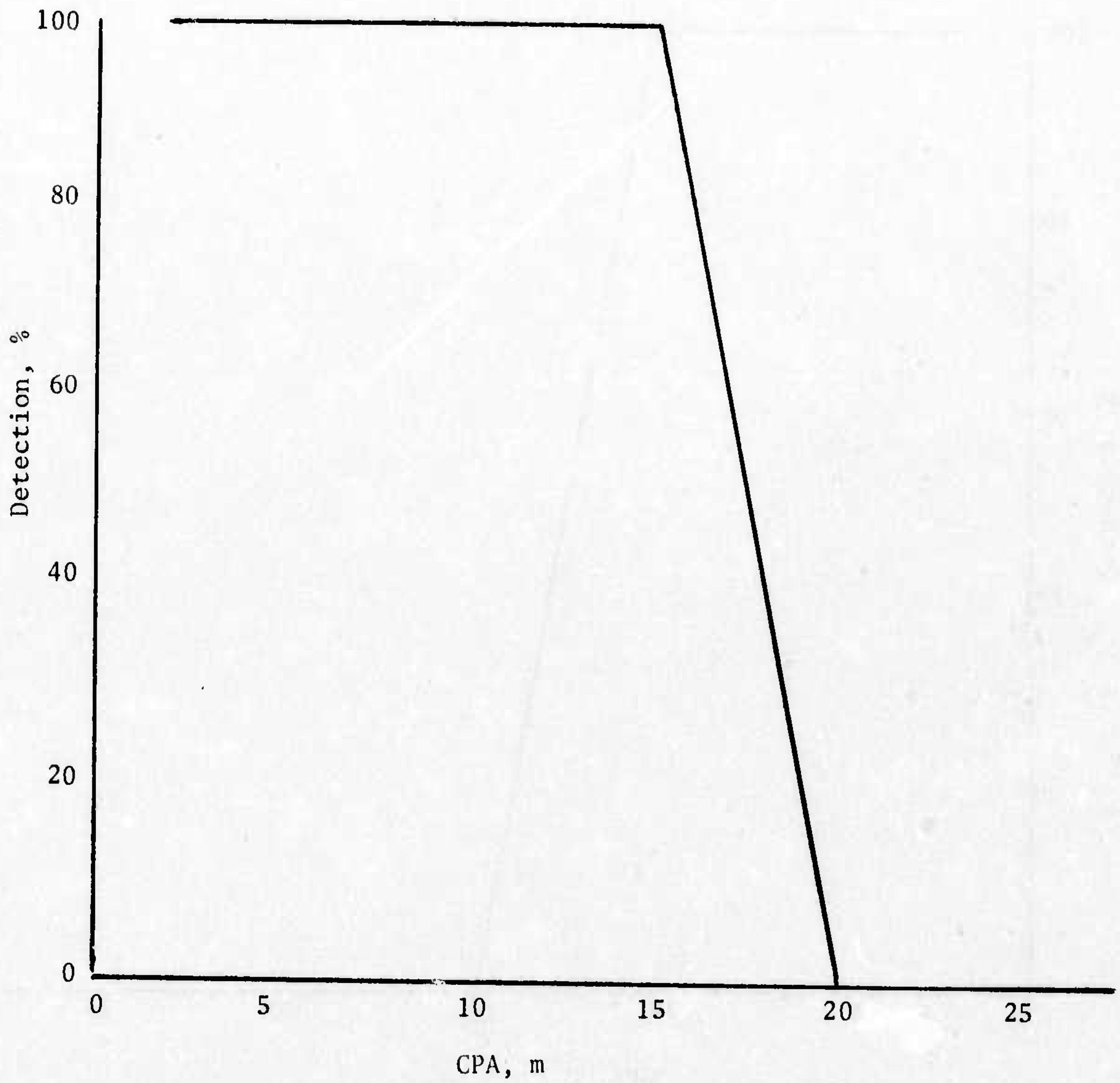

Figure 19. Percent Detection Versus CPA for Matrix Element 38

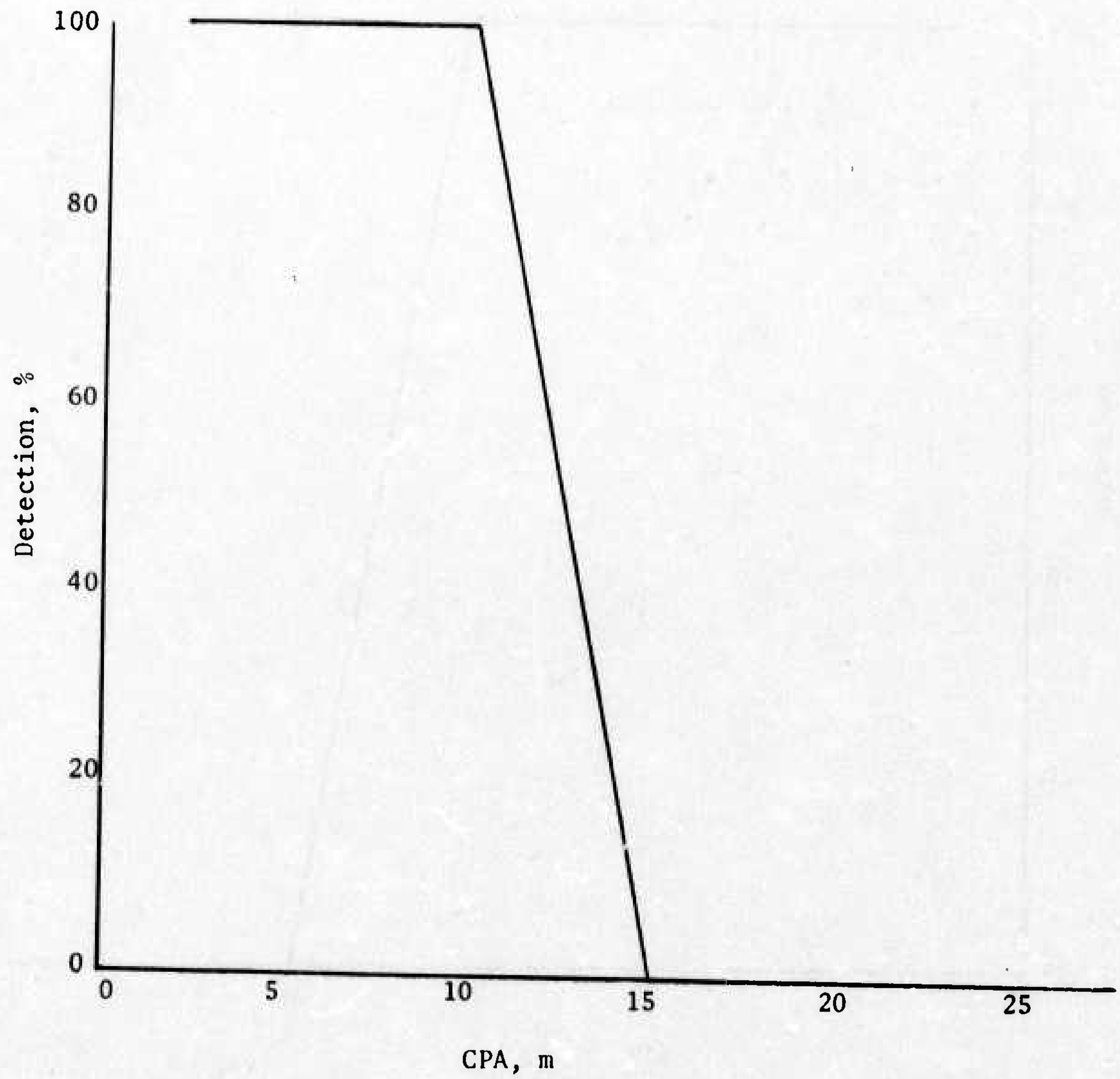

Figure 20. Percent Detection Versus CPA for Matrix Element 41

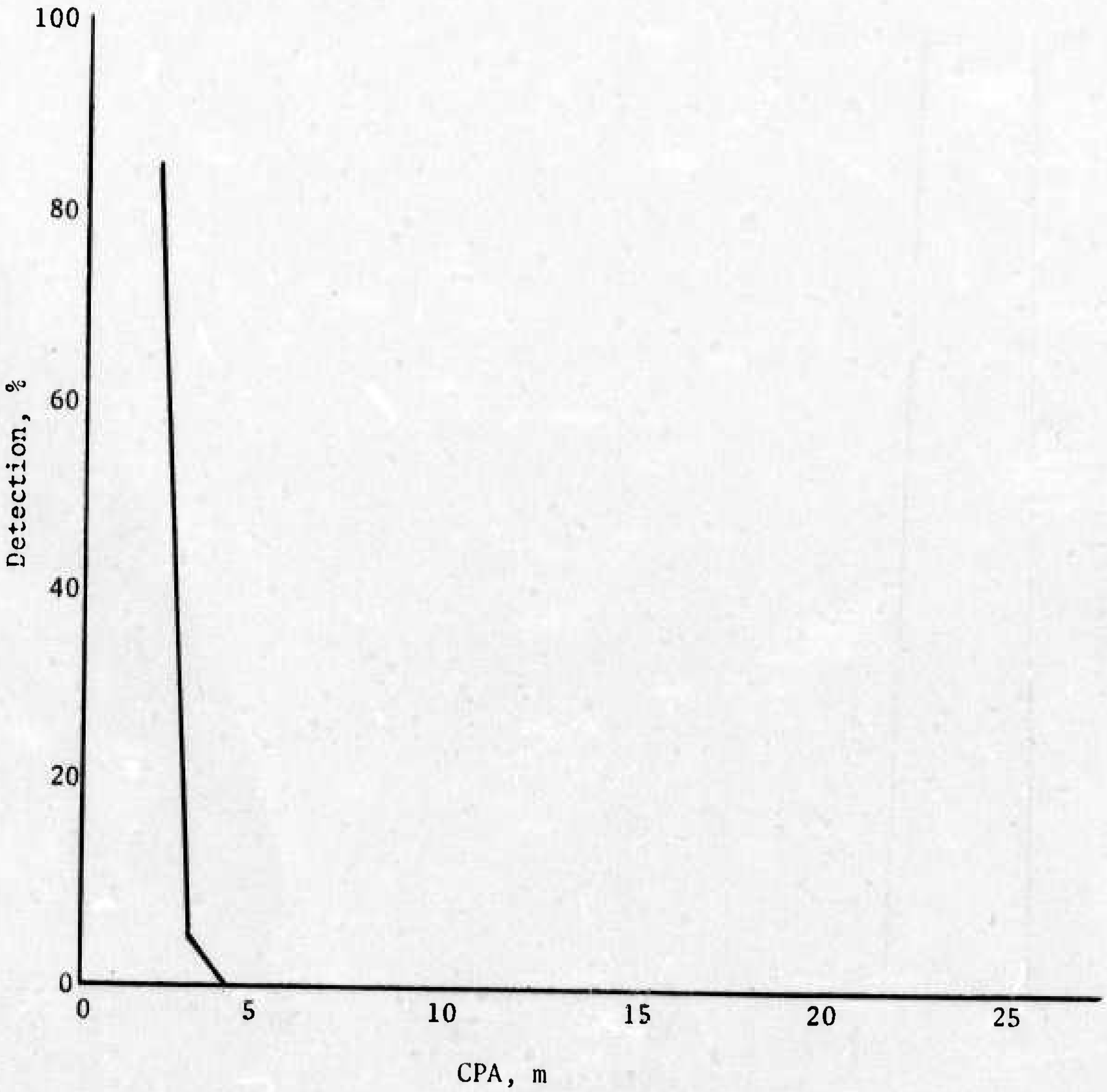

Figure 21. Percent Detection Versus CPA for Matrix Element 45

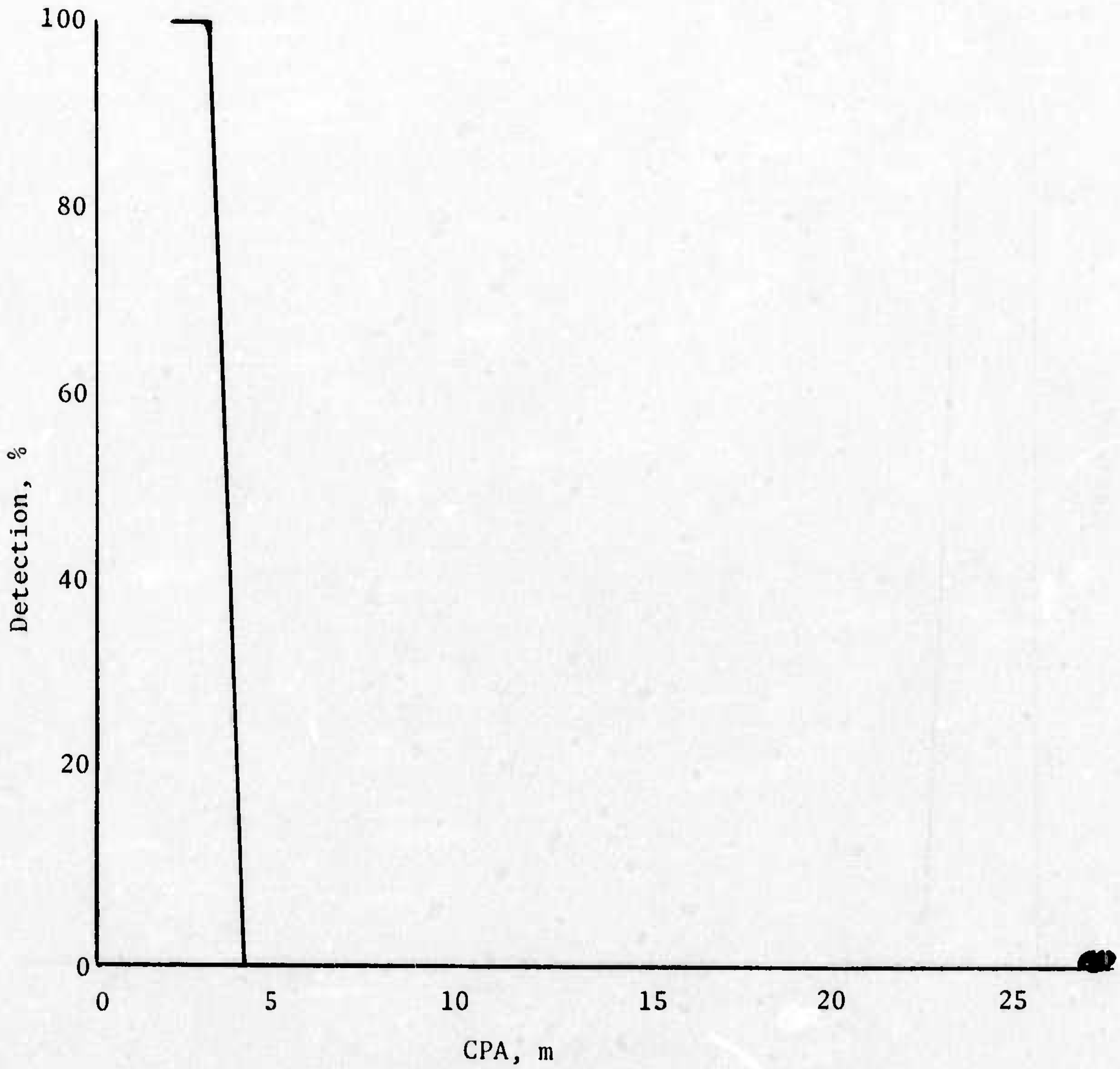

Figure 22. Percent Detection Versus CPA for Matrix Element 46

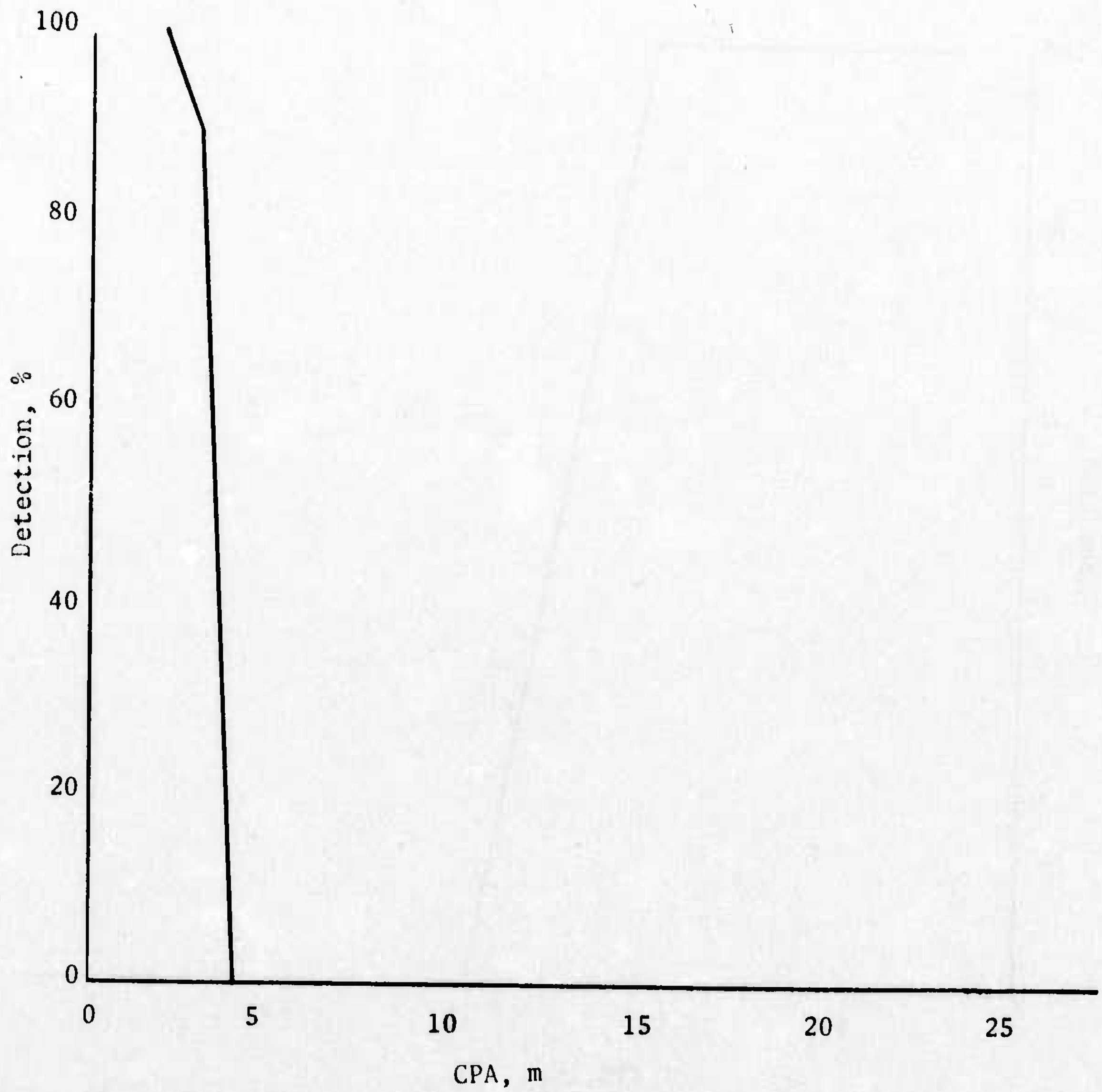

Figure 23. Percent Detection Versus CPA for Matrix Element 47

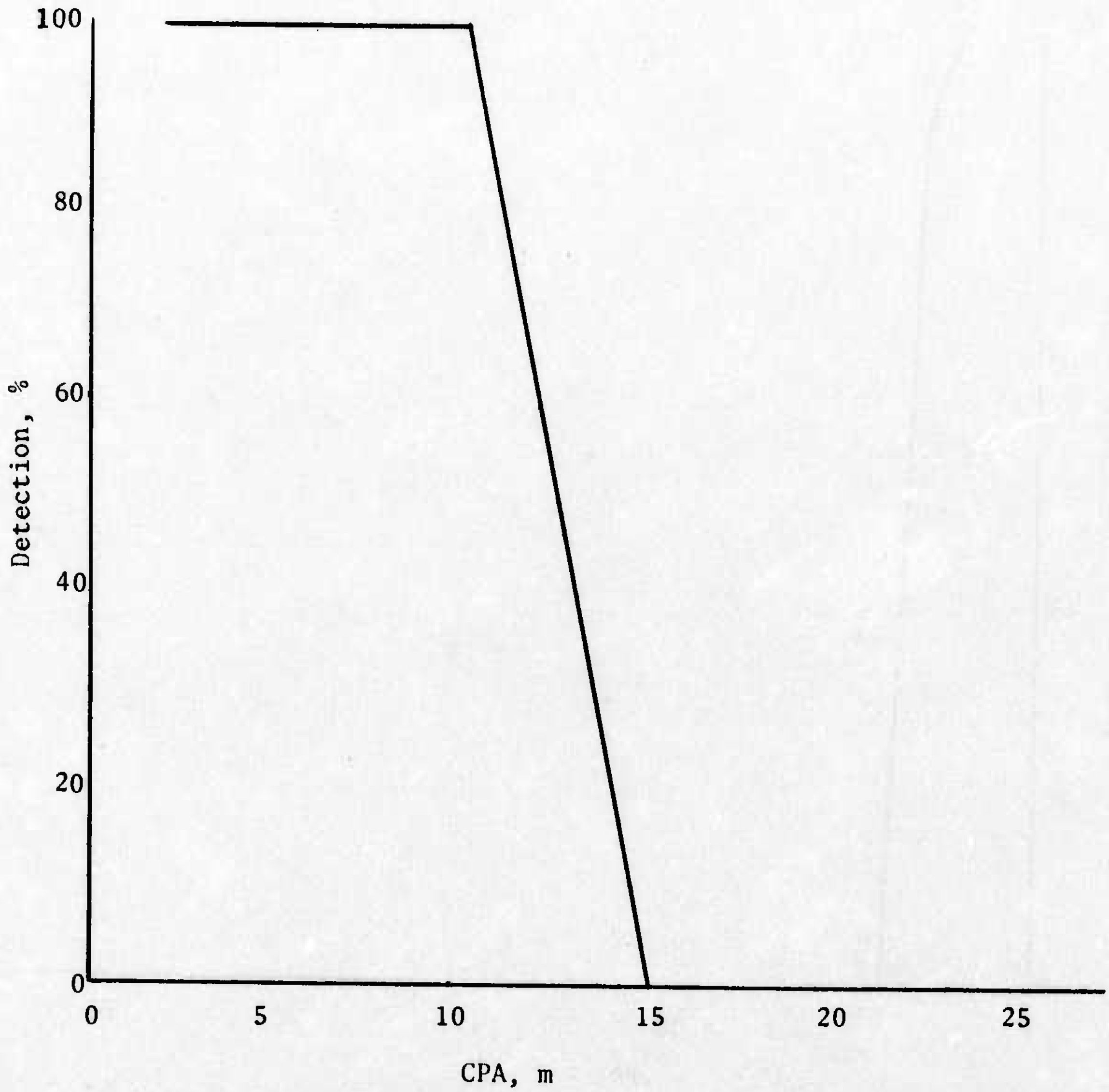

Figure 24. Percent Detection Versus CPA for Matrix Element 53

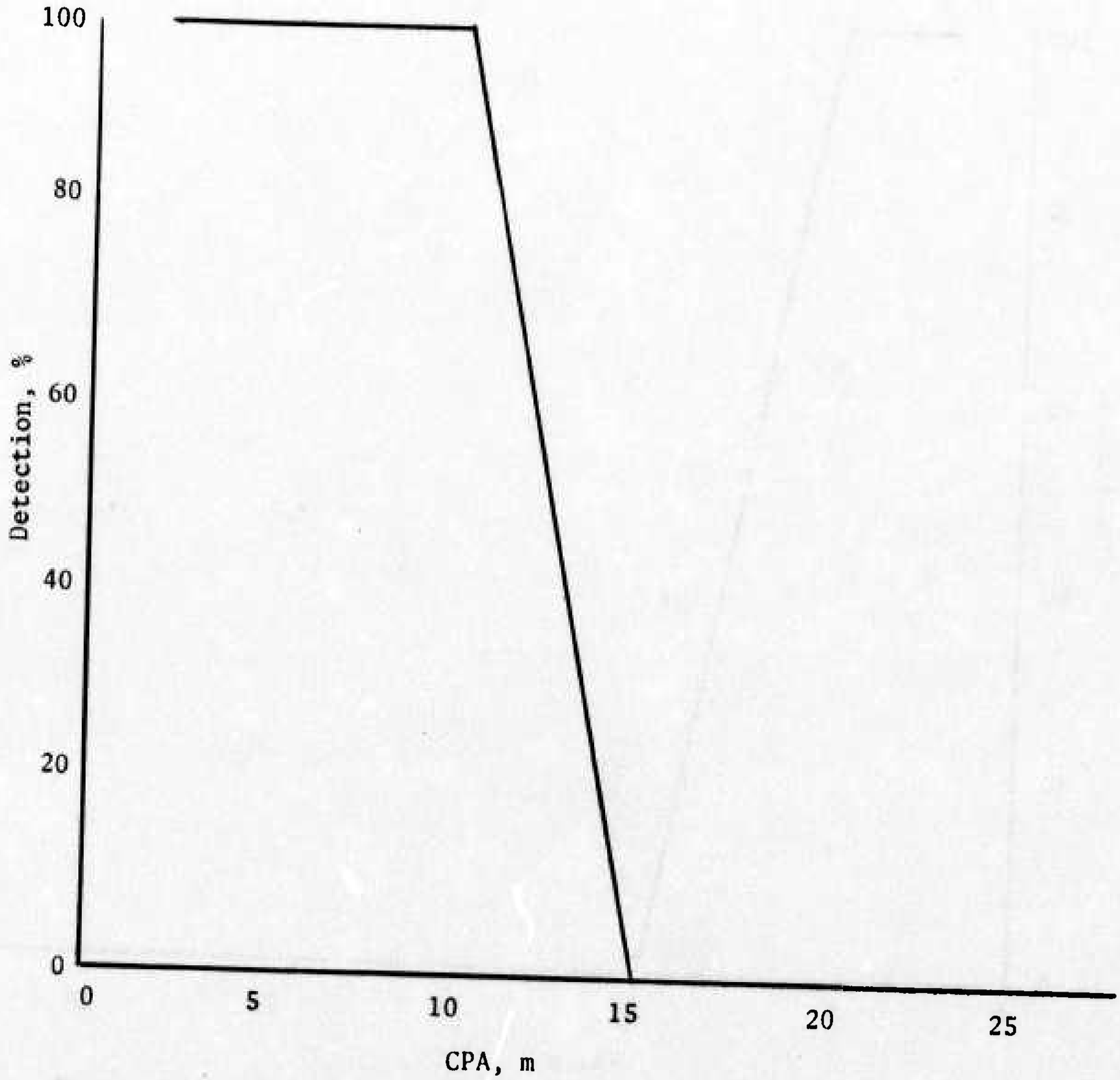

Figure 25. Percent Detection Versus CPA for Matrix Element 54

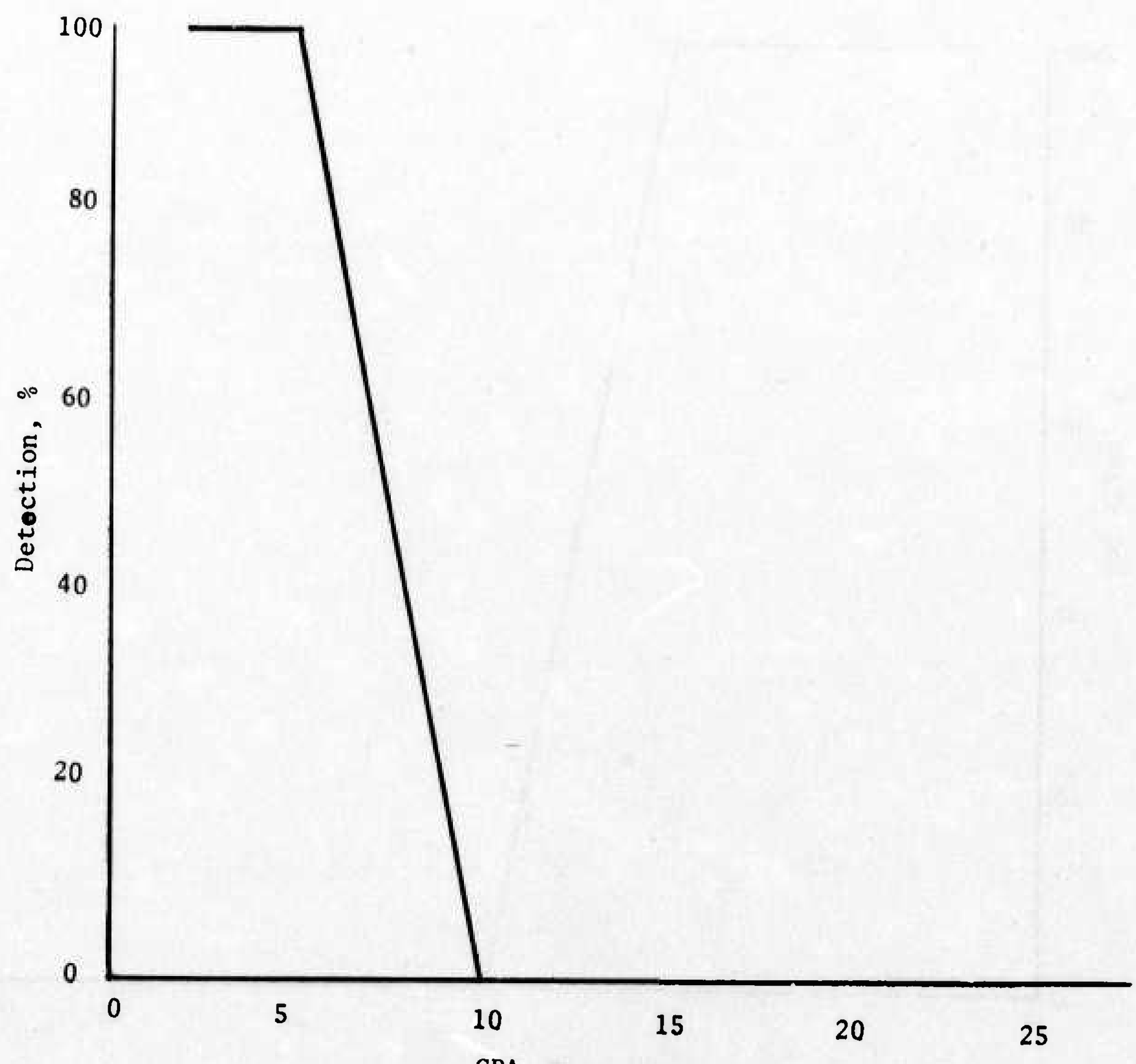

Figure 26. Percent Detection Versus CPA for Matrix Element 55

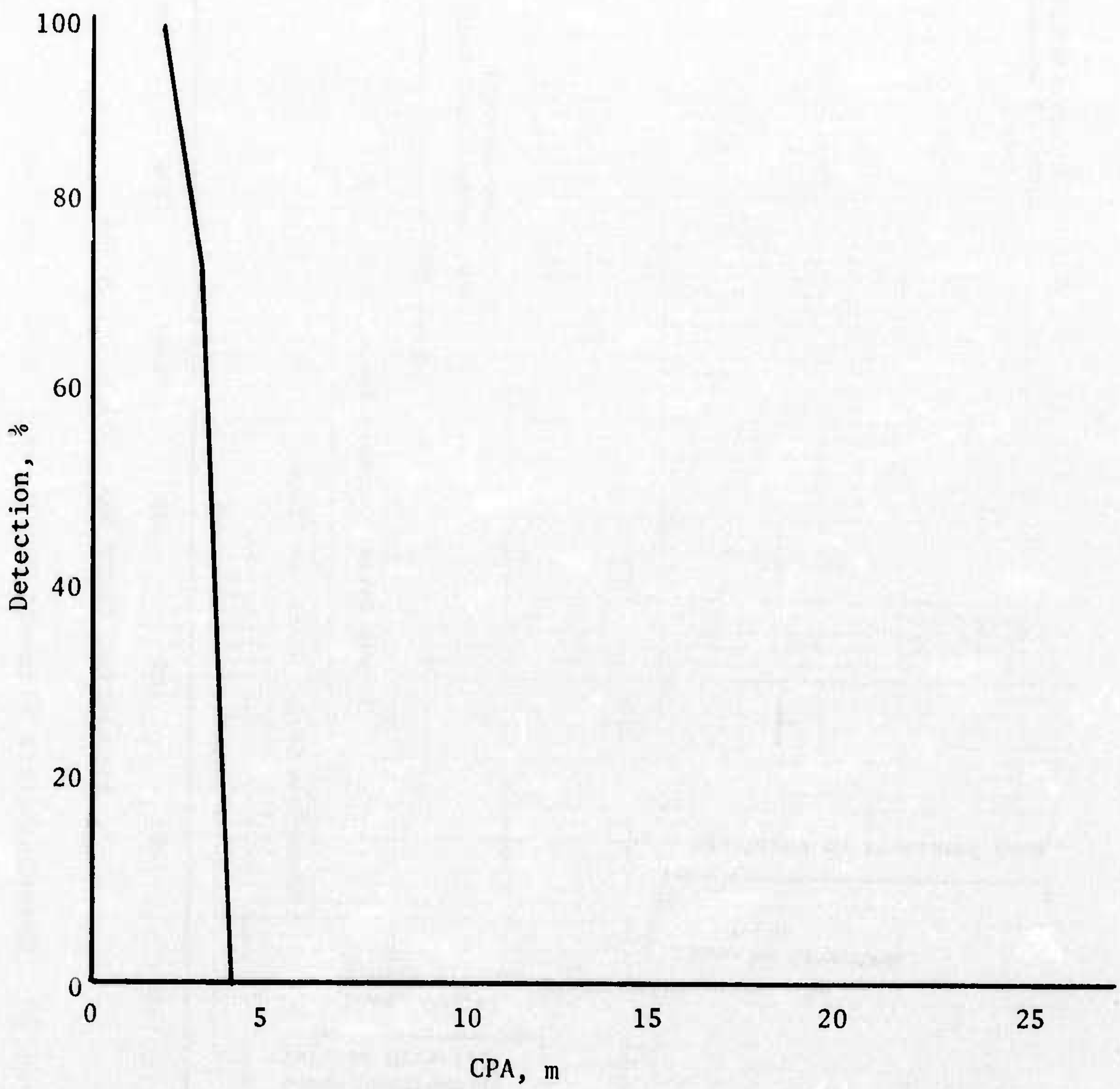

Figure 27. Percent Detection Versus CPA for Matrix Element 56

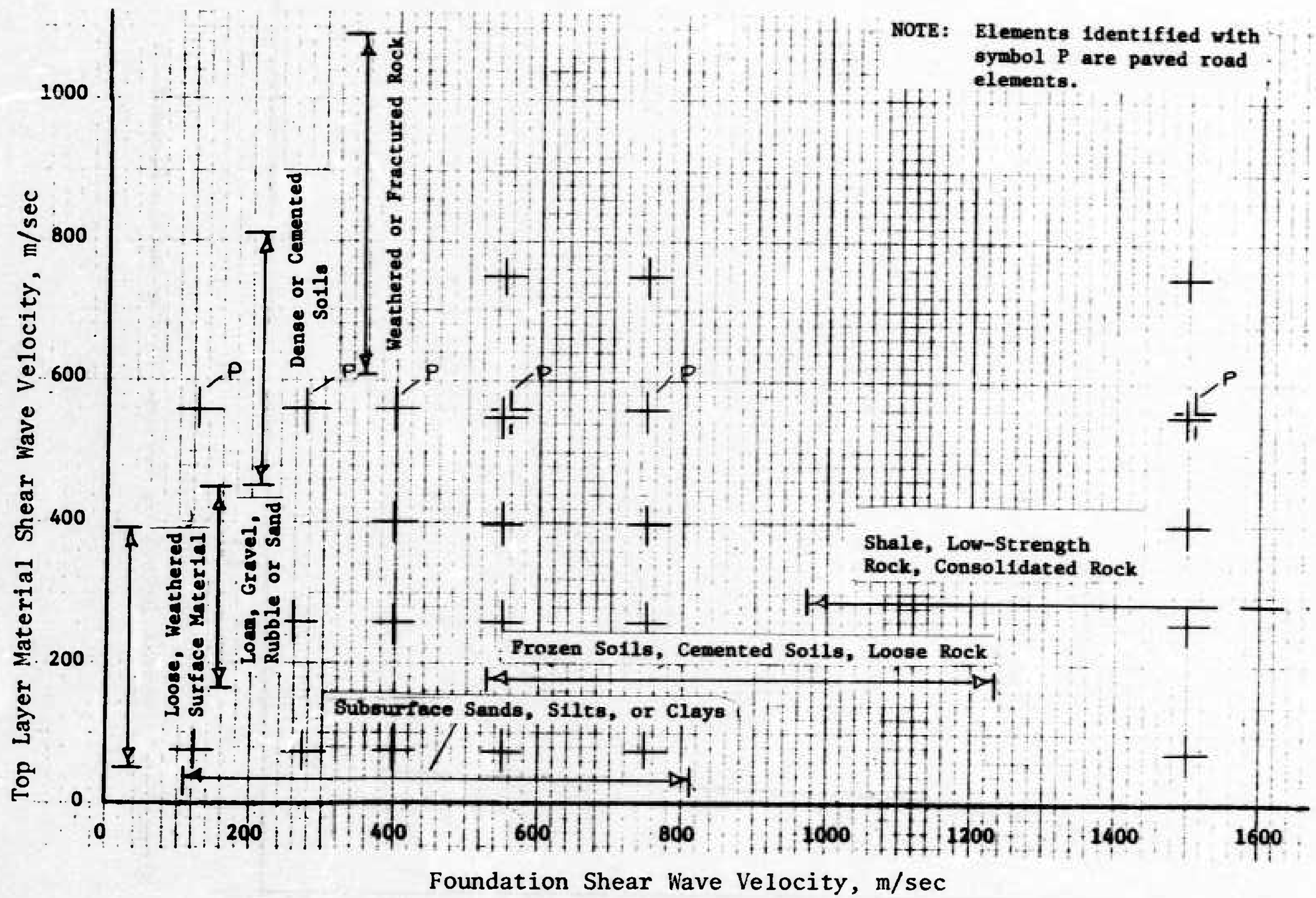

Figure 28. Terrain Matrix Elements Displayed in Shear Wave Space

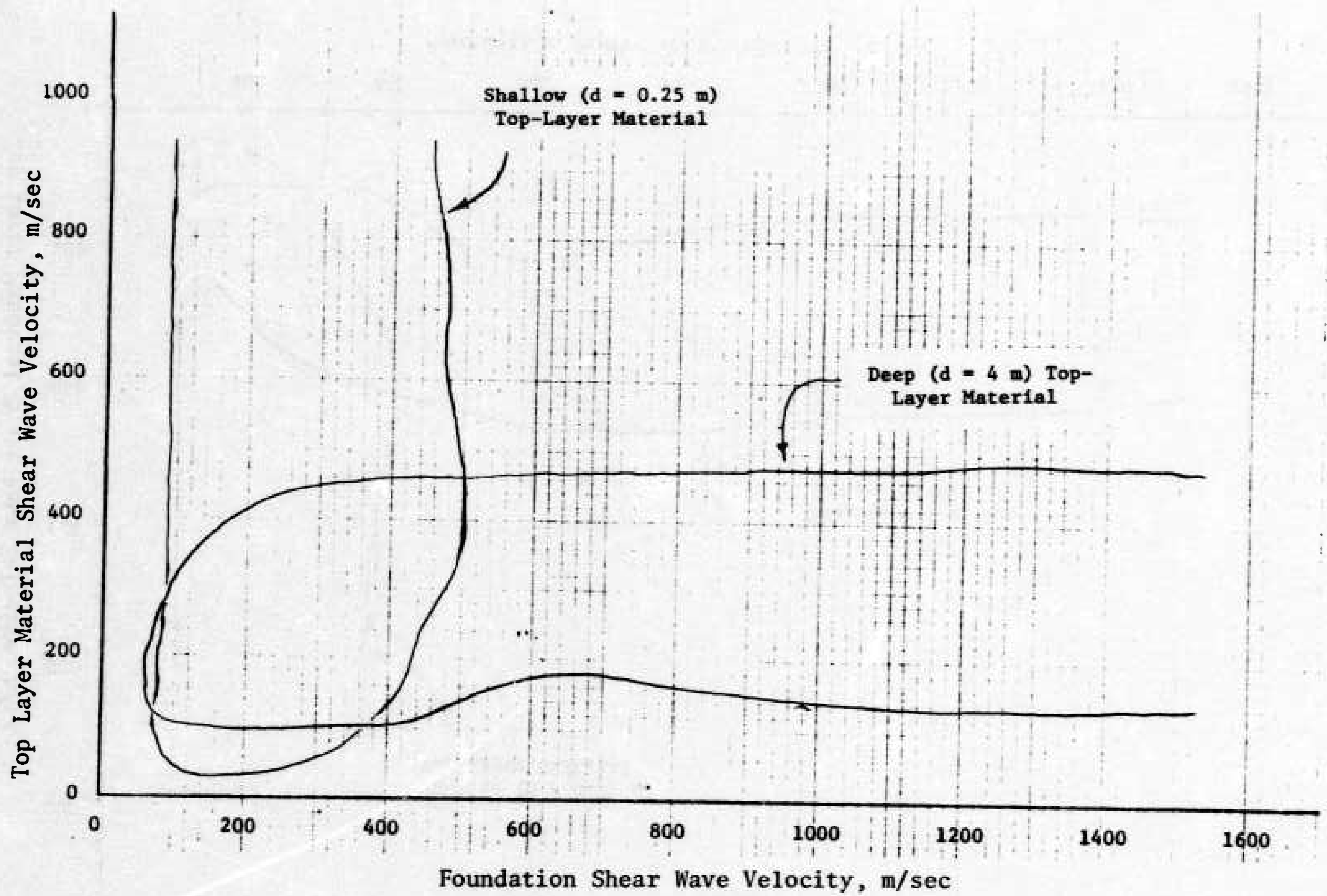

Figure 29. Detection Fnvelopes for 5-m CPA Lines

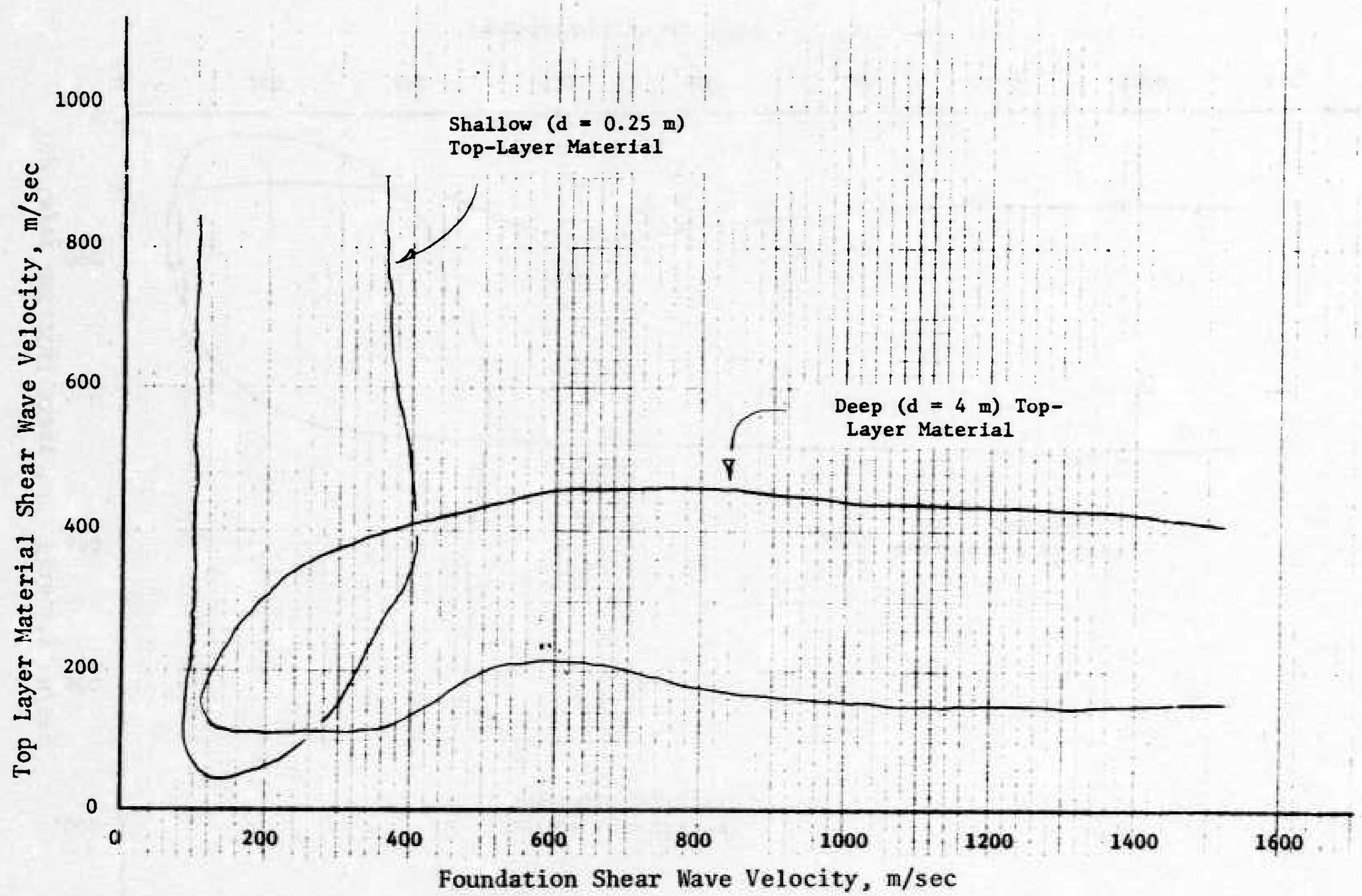

Figure 30. Detection Envelopes for 10-m CPA Lines

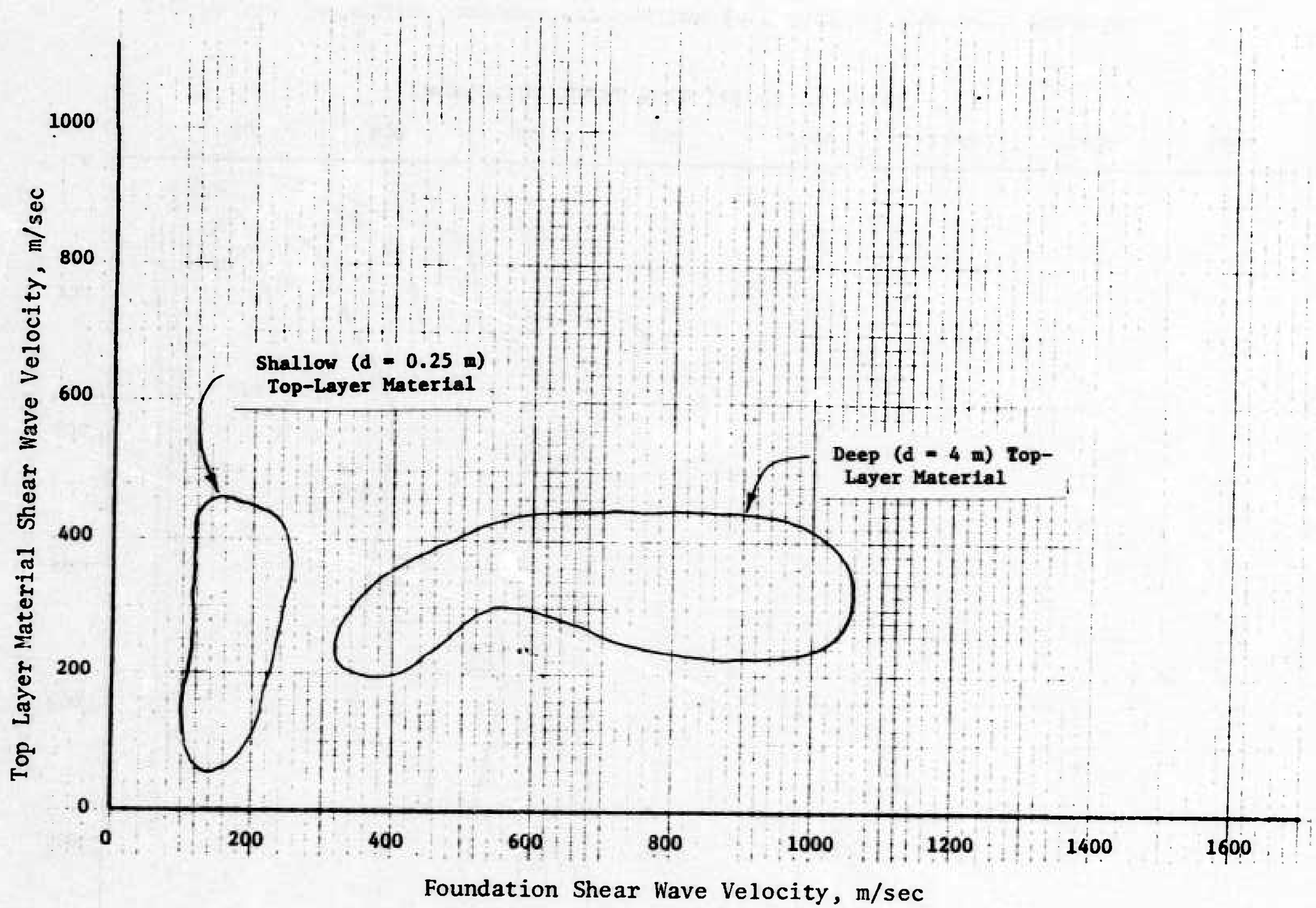

Figure 31. Detection Envelopes for 15-m CPA Lines

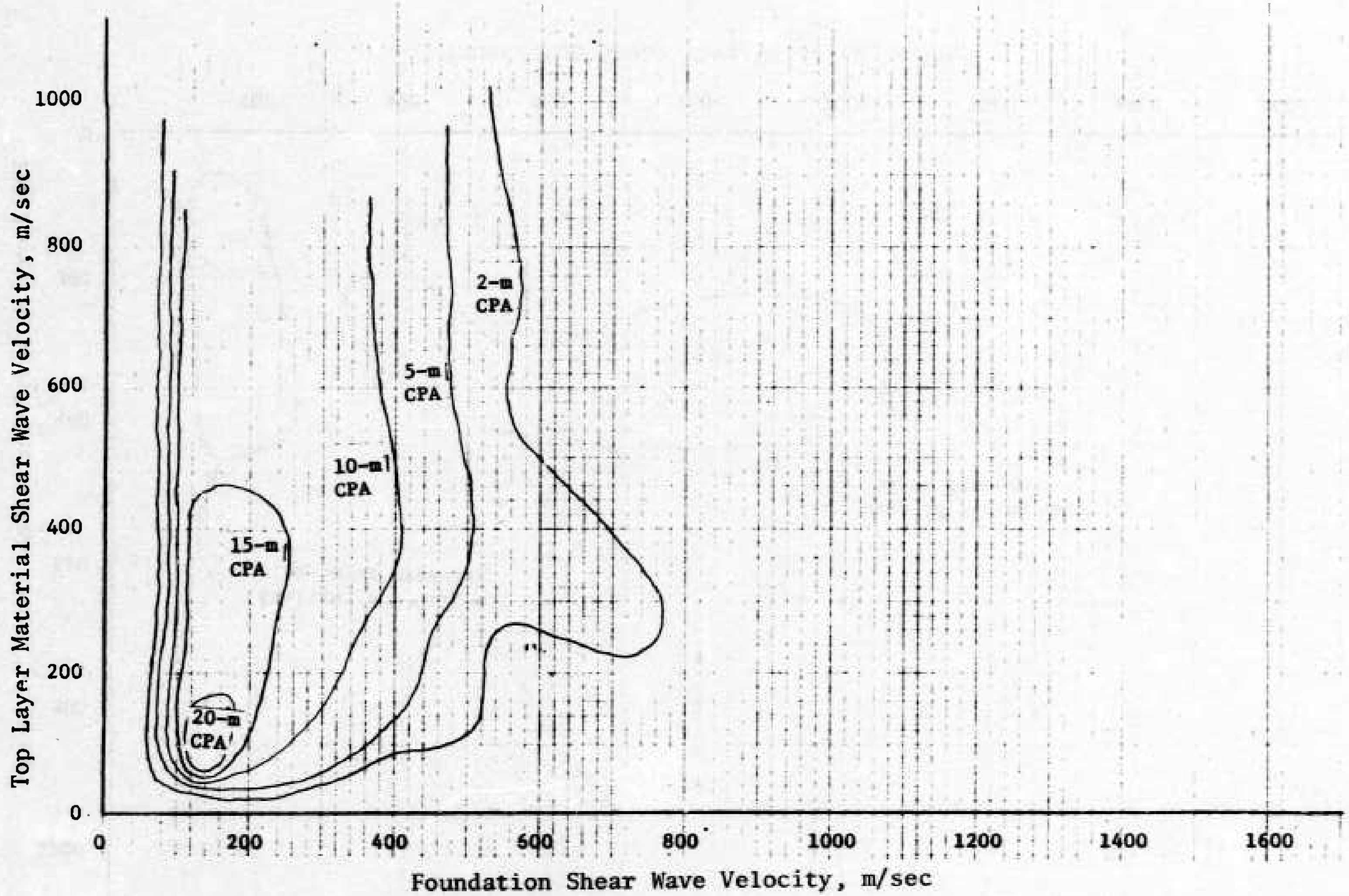

Figure 32. Detection Contours for Shallow (d = 0.25 m) Top-Layer Material

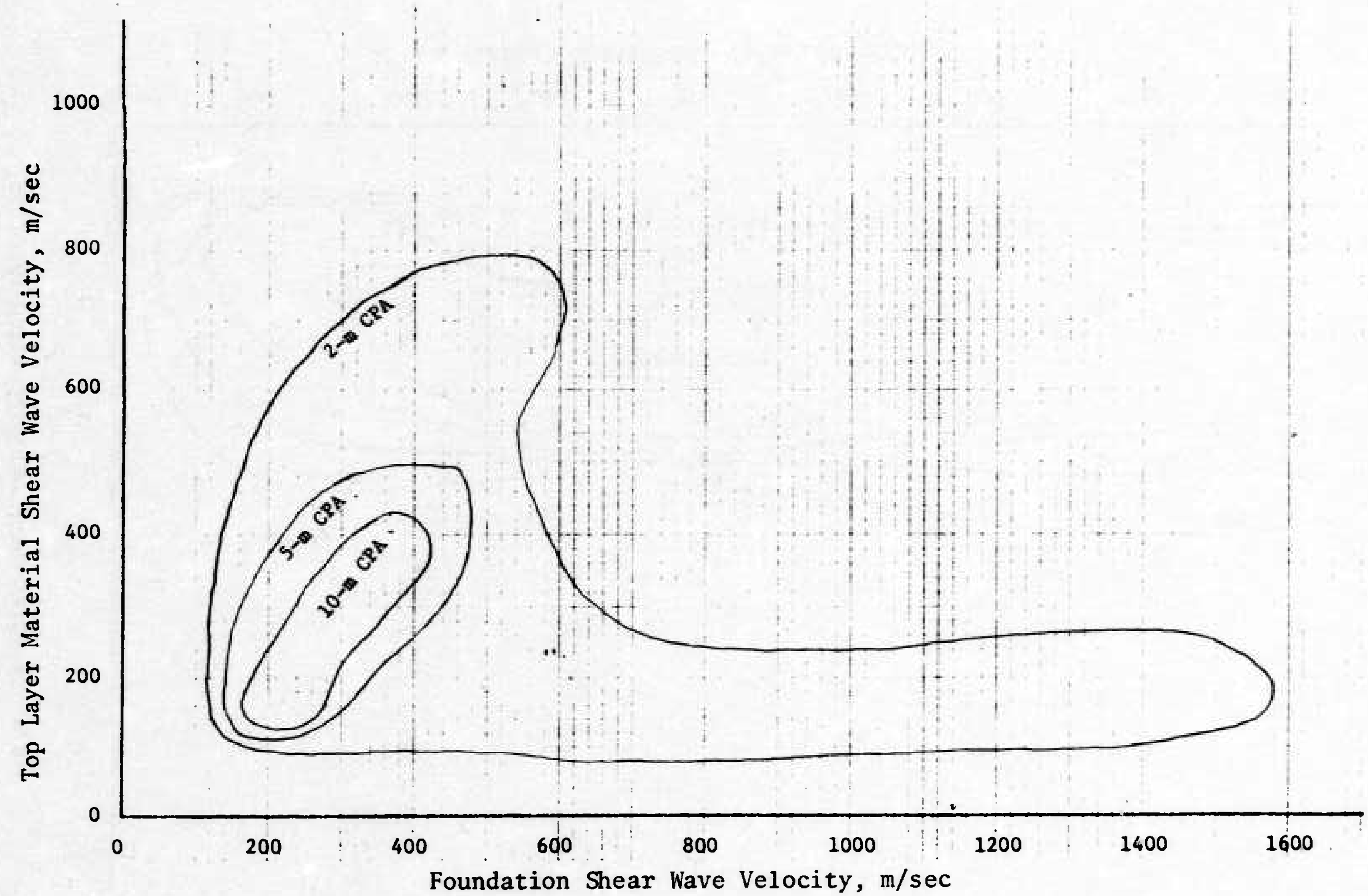

Figure 33. Detection Contours for Intermediate (d = 1.5 m) Top-Layer Material

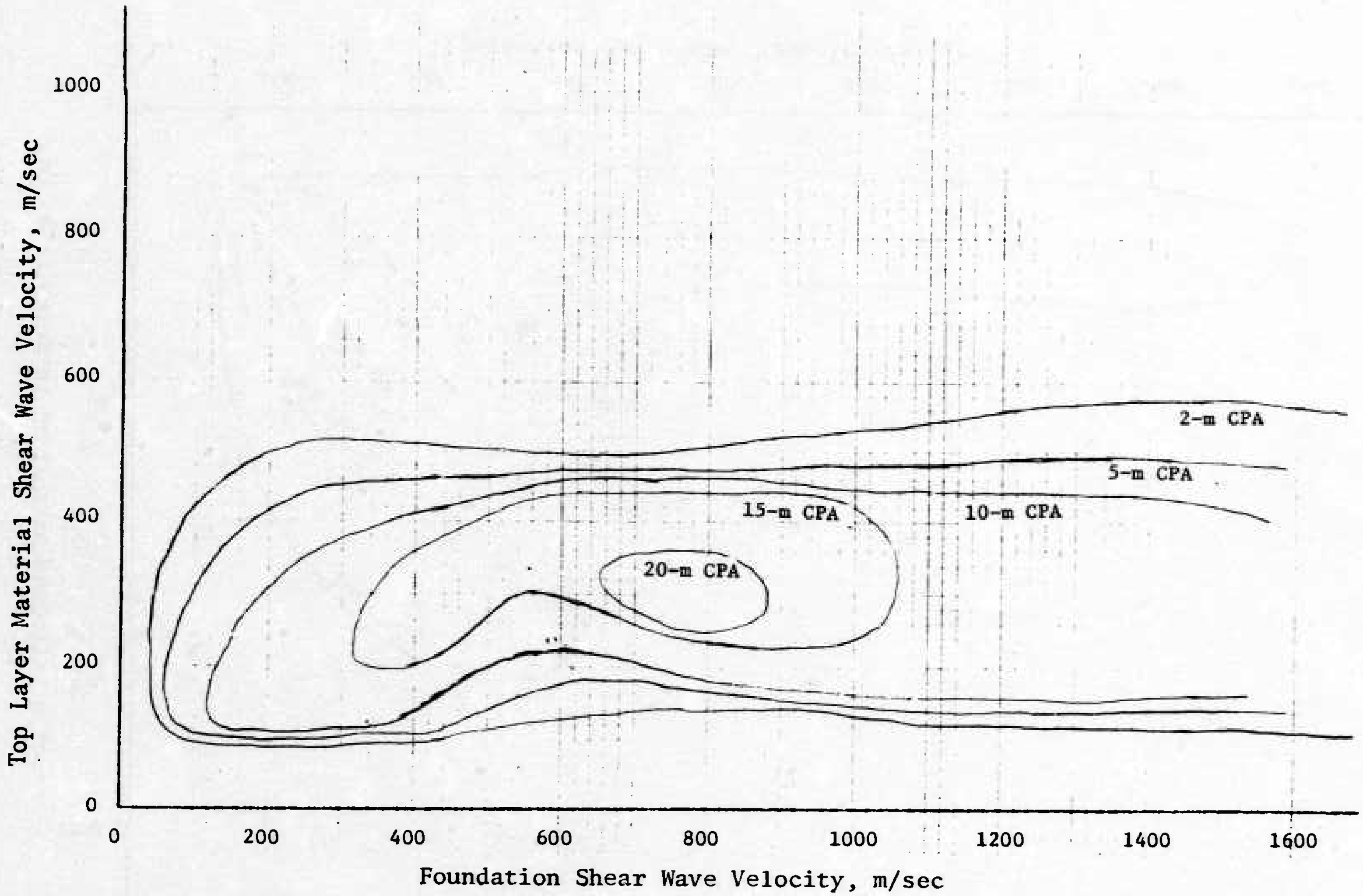

Figure 34. Detection Contours for Deep (d = 4 m) Top-Layer Material

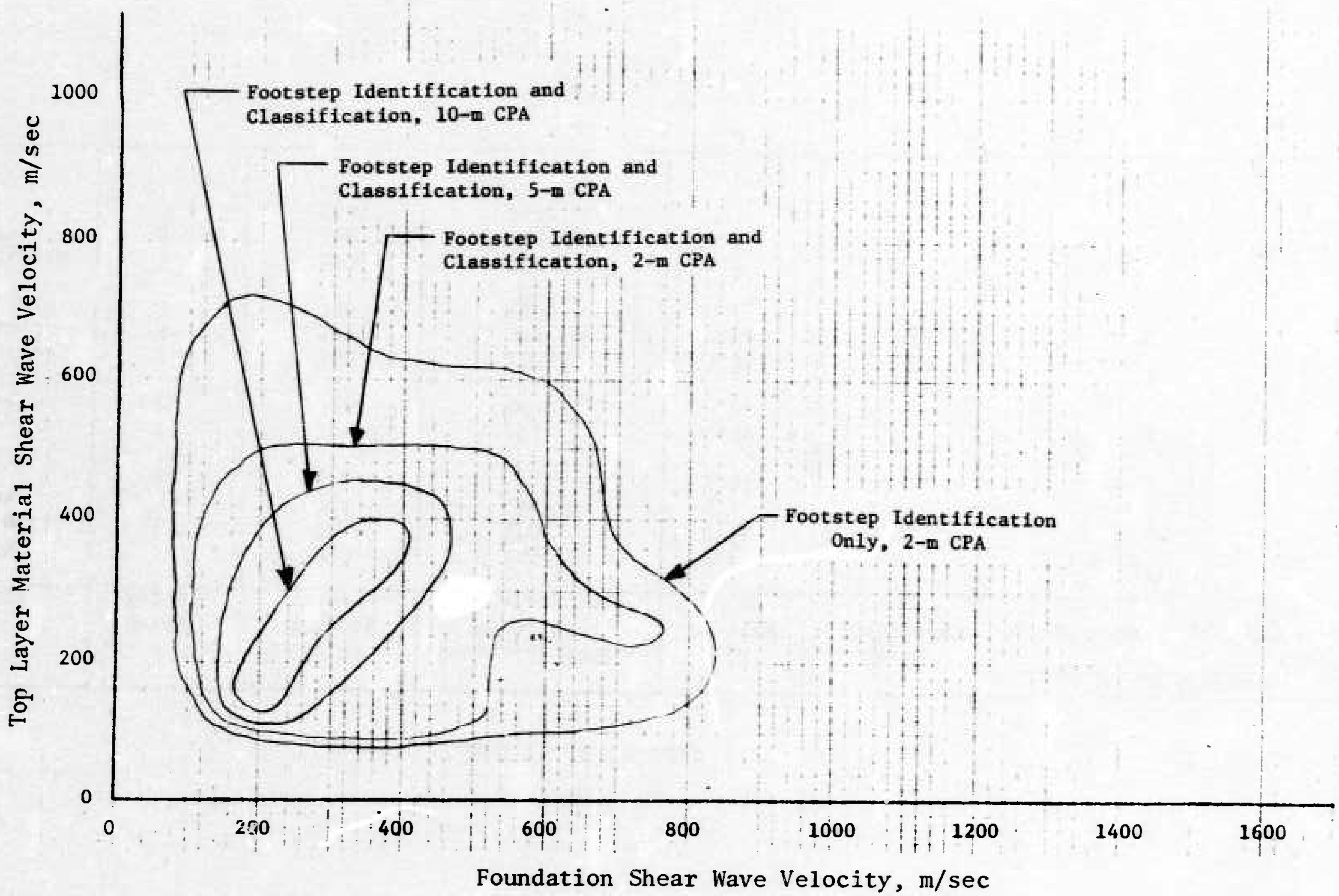

Figure 35. Contour Lines for Operation Independent of Layer Thickness

TABLE 1. SITE DATA

Site	Layer Number	Shear Wave Velocity m/sec	Compression Wave Velocity m/sec	Bulk Density g/cm3	Layer Thickness m	Surface Rigidity	
						Spring Constant N/m	Maximum Deformation m
WES Vicksburg, Miss.	1	250	450	1.9	0.15	3.5×10^5	10
	2	95	150	1.86	0.85		
	3	200	450	1.9	2.4		
	4	200	1475	1.93	---		
Eglin AFB, Fla.	1	100	205	1.89	3.6	2.85×10^5	10
	2	176	440	2.0	---		
Honeywell Hopkins, Minn.	1	300	1000	1.78	0.05	2.7×10^5	10
	2	137	342	1.83	7.95		
	3	720	1800	2.3	---		
Nellis AFB Nev.	1	222	500	1.6	1.3	4.9×10^5	10
	2	360	900	1.7	2.9		
	3	650	1330	2.3	---		

TABLE 2. TERRAIN FACTORS USED IN TERRAIN MATRIX

Terrain Matrix Element	Characteristics of Surface Material: Surface Rigidity: Spring Constant N/m	Characteristics of Surface Material: Surface Rigidity: Maximum Deformation m	Characteristics of Surface Material: Roughness rms Elevation cm	Characteristics of Top-Layer Material: Compression Wave Velocity m/sec	Characteristics of Top-Layer Material: Shear Wave Velocity m/sec	Characteristics of Top-Layer Material: Bulk Density g/cm^3	Characteristics of Top-Layer Material: Layer Thickness m	Characteristics of Second Layer (Subbase) Material: Roughness rms Elevation cm	Characteristics of Second Layer (Subbase) Material: Shear Wave Velocity m/sec	Characteristics of Second Layer (Subbase) Material: Bulk Density g/cm^3	Characteristics of Second Layer (Subbase) Material: Layer Thickness m	Characteristics of Foundation Material: Compression Wave Velocity m/sec	Characteristics of Foundation Material: Shear Wave Velocity m/sec	Characteristics of Foundation Material: Bulk Density g/cm^3	Terrain Description
Cross-Country Terrain Conditions															
1	$1.8x10^5$	0.1	5.08	150	75	1.6	0.25	NA	NA	NA	NA	300	125	1.7	
2	$1.8x10^5$	0.1	5.08	150	75	1.6	1.5					300	125	1.7	Recently cultivated fields, loose cohesionless topsoils, or organic saturated clays overlying dry sands, moist loams, slightly sandy or gravelly soft clays.
3	$1.8x10^5$	0.1	5.08	150	75	1.6	4.0					300	125	1.7	
4	$1.8x10^5$	0.1	5.08	150	75	1.6	0.25					680	275	2.0	
5	$1.8x10^5$	0.1	5.08	150	75	1.6	1.5					680	275	2.0	Recently cultivated fields, loose cohesionless topsoils, or organic saturated clays overlying dry gravel, moist sandy or gravelly loams, medium clays.
6	$1.8x10^5$	0.1	5.08	150	75	1.6	4.0					680	275	2.0	
7	$1.8x10^5$	0.1	5.08	150	75	1.6	0.25					1450	400	2.05	
8	$1.8x10^5$	0.1	5.08	150	75	1.6	1.5					1450	400	2.05	Recently cultivated fields, loose cohesionless topsoils, or organic saturated clays overlying wet medium dense sands, moist medium gravels, fat gravelly clay (till).
9	$1.8x10^5$	0.1	5.08	150	75	1.6	4.0					1450	400	2.05	
10	$1.8x10^5$	0.1	5.08	150	75	1.6	0.25					2000	550	1.80	
11	$1.8x10^5$	0.1	5.08	150	75	1.6	1.5					2000	550	1.80	Recently cultivated fields, loose cohesionless topsoils, or organic saturated clays overlying frozen silty or clayey loam, dense soil with high water table.
12	$1.8x10^5$	0.1	5.08	150	75	1.6	4.0					2000	550	1.80	
13	$1.8x10^5$	0.1	5.08	150	75	1.6	0.25					2000	750	2.1	
14	$1.8x10^5$	0.1	5.08	150	75	1.6	1.5					2000	750	2.1	Recently cultivated fields, loose cohesionless topsoils, or organic saturated clays overlying dense sands and gravels, cemented residual soils, weathered rock, hard clay.
15	$1.8x10^5$	0.1	5.08	150	75	1.6	4.0					2000	750	2.1	

TABLE 2. (CONTINUED)

Terrain Matrix Element	Characteristics of Surface Material: Surface Rigidity: Spring Constant N/m	Surface Rigidity: Maximum Deformation m	Roughness rms Elevation cm	Characteristics of Top-Layer Material: Compression Wave Velocity m/sec	Shear Wave Velocity m/sec	Bulk Density g/cm^3	Layer Thickness m	Characteristics of Second Layer (Subbase) Material: Roughness rms Elevation cm	Shear Wave Velocity m/sec	Bulk Density g/cm^3	Layer Thickness m	Characteristics of Foundation Material: Compression Wave Velocity m/sec	Shear Wave Velocity m/sec	Bulk Density g/cm^3	Terrain Description
								Cross-Country Terrain Conditions (Continued)							
16	1.8×10^5	0.1	5.08	150	75	1.6	0.25	NA	NA	NA	NA	5000	1500	2.5	Recently cultivated fields, loose cohesionless topsoils, or organic saturated clays overlying competent or slightly weathered rock.
17	1.8×10^5	0.1	5.08	150	75	1.6	1.5					5000	1500	2.5	
18	1.8×10^5	0.1	5.08	150	75	1.6	4.0					5000	1500	2.5	
19	5.4×10^5	0.075	3.05	655	260	1.7	10.0					-	-	-	Dry loose gravel, medium sands, moist sandy or silty clays.
20	5.4×10^5	0.075	3.05	655	260	1.7	0.25					1450	400	2.05	Dry loose gravel, medium sands, moist sandy or silty clays overlying wet medium-dense sand, moist medium gravel, fat gravelly clays (till).
21	5.4×10^5	0.075	3.05	655	260	1.7	1.5					1450	400	2.05	
22	5.4×10^5	0.075	3.05	655	260	1.7	4.0					1450	400	2.05	
23	5.4×10^5	0.075	3.05	655	260	1.7	0.25					2000	550	1.8	Dry loose gravel, medium sands, moist sandy or silty clays overlying frozen silty or clayey loam, dense cohesionless soils with high water table.
24	5.4×10^5	0.075	3.05	655	260	1.7	1.5					2000	550	1.8	
25	5.4×10^5	0.075	3.05	655	260	1.7	4.0					2000	550	1.8	
26	5.4×10^5	0.075	3.05	655	260	1.7	0.25					2000	750	2.1	Dry, loose gravles: medium sands; moist sands or silty clays overlying dense sands and gravels: cemented residual soils: weathered rock; hard clays.
27	5.4×10^5	0.075	3.05	655	260	1.7	1.5					2000	750	2.1	
28	5.4×10^5	0.075	3.05	655	260	1.7	4.0					2000	750	2.1	
29	5.4×10^5	0.075	3.05	655	260	1.7	0.25					5000	1500	2.5	Dry. loose gravels: medium sands: moist sands or silty clays overlying competent or slightly weathered rock.
30	5.4×10^5	0.075	3.05	655	260	1.7	1.5					5000	1500	2.5	
31	5.4×10^5	0.075	3.05	655	260	1.7	4.0					5000	1500	2.5	
32	12.6×10^5	0.05	1.90	1450	400	1.9	10.0					-	-	-	Wet, medium-dense sands: moist, medium gravels; fat gravelly clays (till).

TABLE 2. (CONTINUED)

Terrain Matrix Element	Characteristics of Surface Material: Surface Rigidity: Spring Constant N/m	Maximum Deforma- tion m	Roughness rms Elevation cm	Characteristics of Top-Layer Material: Compres- sion Wave Velocity m/sec	Shear Wave Velocity m/sec	Bulk Density g/cm^3	Layer Thick- ness m	Characteristics of Second Layer (Subbase) Material: Roughness rms Elevation cm	Shear Wave Velocity m/sec	Bulk Density g/cm^3	Layer Thick- ness m	Characteristics of Foundation Material: Compres- sion Wave Velocity m/sec	Shear Wave Velocity m/sec	Bulk Density g/cm^3	Terrain Description
Cross-Country Terrain Conditions (Continued)															
33	$12.6x10^5$	0.05	1.90	1450	400	1.9	0.25	NA	NA	NA	NA	2000	550	1.8	Wet, medium-dense sands; moist medium gravels; heavy gravelly clays (till) overlying frozen silty or clayey loam; dense cohesionless soil with high water table.
34	$12.6x10^5$	0.05	1.90	1450	400	1.9	1.5					2000	550	1.8	
35	$12.6x10^5$	0.05	1.90	1450	400	1.9	4.0					2000	550	1.8	
36	$12.6x10^5$	0.05	1.90	1450	400	1.9	0.25					2000	750	2.1	Wet, medium-dense sands; moist medium gravels; heavy gravelly clays (till) overlying dense sands and gravels; cemented residual soils; weathered rock; hard clay.
37	$12.6x10^5$	0.05	1.90	1450	400	1.9	1.5					2000	750	2.1	
38	$12.6x10^5$	0.05	1.90	1450	400	1.9	4.0					2000	750	2.1	
39	$12.6x10^5$	0.05	1.90	1450	400	1.9	0.25					5000	1500	2.5	Wet medium-dense sands, moist medium gravels, fat gravelly clays (till) overlying competent or slightly weathered rock.
40	$12.6x10^5$	0.05	1.90	1450	400	1.9	1.5					5000	1500	2.5	
41	$12.6x10^5$	0.05	1.90	1450	400	1.9	4.0					5000	1500	2.5	
42	$25.2x10^5$	0.025	2.54	2000	550	1.8	10.0					-	-	-	Frozen silty or clayey loam, dense cohesionless soil with high water table.
43	$25.2x10^5$	0.025	2.54	2000	550	1.8	0.25					5000	1500	2.5	Frozen silty or clayey loam, dense cohesionless soil with high water table overlying competent or slightly weathered rock.
44	$25.2x10^5$	0.025	2.54	2000	550	1.8	1.5					5000	1500	2.5	
45	$25.2x10^5$	0.025	2.54	2000	550	1.8	4.0					5000	1500	2.5	
46	$18.9x10^5$	0.03	3.81	2000	750	2.1	0.25					2000	550	1.8	Dense sands and gravels, cemented residual soils, hard clay overlying frozen silty or clayey loam, dense cohesionless soils with high water table.
47	$18.9x10^5$	0.03	3.81	2000	750	2.1	1.5					2000	550	1.8	
48	$18.9x10^5$	0.03	3.81	2000	750	2.1	4.0					2000	550	1.8	
49	$18.9x10^5$	0.03	3.81	2000	750	2.1	10.0					-	-	-	Dense sands and gravels, cemented residual soils, weathered rock.

TABLE 2. (CONCLUDED)

Terrain Matrix Element	Characteristics of Surface Material: Surface Rigidity: Spring Constant N/m	Characteristics of Surface Material: Surface Rigidity: Maximum Deformation m	Characteristics of Surface Material: Roughness rms Elevation cm	Characteristics of Top-Layer Material: Compression Wave Velocity m/sec	Characteristics of Top-Layer Material: Shear Wave Velocity m/sec	Characteristics of Top-Layer Material: Bulk Density g/cm^3	Characteristics of Top-Layer Material: Layer Thickness m	Characteristics of Second Layer (Subbase) Material: Roughness rms Elevation cm	Characteristics of Second Layer (Subbase) Material: Shear Wave Velocity m/sec	Characteristics of Second Layer (Subbase) Material: Bulk Density g/cm^3	Characteristics of Second Layer (Subbase) Material: Layer Thickness m	Characteristics of Foundation Material: Compression Wave Velocity m/sec	Characteristics of Foundation Material: Shear Wave Velocity m/sec	Characteristics of Foundation Material: Bulk Density g/cm^3	Terrain Description
Cross-Country Terrain Conditions (Continued)															
50	18.9×10^5	0.3	3.81	2000	750	2.1	0.25	NA	NA	NA	NA	5000	1500	2.5	
51	18.9×10^5	0.3	3.81	2000	750	2.1	1.5					5000	1500	2.5	Hard clay, dense sands and gravels, cemented residual soils, weathered rock overlying competent or slightly weathered rock.
52	18.9×10^5	0.3	3.81	2000	750	2.1	4.0					5000	1500	2.5	
Pavement Conditions*															
53	NA	NA	NA	3600	900	2.5	0.08	0.75	560	2.0	0.60	300	125	1.7	Asphalt pavement with base over dry sands, moist loams, gravel or sandy soft clays
54				3600	900	2.5	0.08	0.75	560	2.0	0.20	680	275	2.0	Asphalt pavement with base over dry cravels; moist sandy or gravelly loams; medium clays.
55				3600	900	2.5	0.08	0.75	560	2.0	0.30	1450	400	2.05	Aspahlt pavement with base over wet medium-dense sands; moist medium gravels; fat gravelly clays.
56				3600	900	2.5	0.08	0.75	560	2.0	1.0	2000	550	1.80	Asphalt pavement with base over frozen silty or clayey loam; dense soils with high water table.
57				3600	900	2.5	0.08	0.75	560	2.0	0.10	2000	750	2.10	Asphalt pavement with base over dense sands and gravels; cement residual soils; weathered rock; hard clay.
58				3600	900	2.5	0.08	0.75	560	2.0	0.10	2000	1500	2.50	Asphalt pavement with base over competent or slightly weathered rock.

*Top layer material is the pavement on the road.

TABLE 3. PROBABILITY OF DETECTION RESULTS

Terrain Matrix Element*	Normalized Probability of Detection,** % — Target-to-Sensor Range, m: 0-5	5-10	10-15	15-20	Probability of Detection† %
1	-††	-	-	100	100
4	100	0	0	0	100
14	82	18	0	0	95
19	75	25	0	0	100
20	100	0	0	0	100
21	100	0	0	0	100
22	-	30	70	0	100
24	100	0	0	0	100
25	-	100	0	0	100
26	100	0	0	0	100
28	-	50	37	12.5	100
30	39	61	0	0	58
31	5	95	0	0	100
32	75	25	0	0	100
33	95	5	0	0	100
34	100	0	0	0	100
35	-	75	25	0	100
38	-	50	50	0	100
41	-	100	0	0	100
45	83	17	0	0	85
46	100	0	0	0	100
47	95	5	0	0	100
53	15	85	0	0	100
54	-	100	0	0	100
55	100	0	0	0	100
56	95	5	0	0	100
				0	

Total Number of Activations = 26

* Any matrix element not listed in this table had zero probability of detection, i.e., in 32 terrain elements out of 58 there was no detection.

** Distribution in percent by range class for all signals identified and classified as footsteps.

† Probability of detection in percent for all signals.

†† Dashes under Target-to-Sensor Ranges indicates that sensor has already made a detection at some larger range and the trial was terminated. If the intruder's footsteps were continued and the sensor logic reset, detection would probably continue through to zero range.

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APPENDIX A

DEFINITIONS OF TERRAIN MATRIX TERMS

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Terrain Factor: A property or characteristic of the terrain that can be described by a single numerical descriptor.

Terrain Matrix: A tabulation or display of all the terrain elements used in the computations.

Terrain Matrix Elements: An aggregate of the terrain factors chosen for a single prediction, i.e. the inputs to the mathematical models for predicting the time- and frequency-domain signals.

Surface Rigidity Spring Constant: Spring constant for linear (elastic) approximation of loading spring. The spring constant is derived from load-deflection curves and is similar to the coefficient of subgrade reaction, k_s, in the literature dealing with pavement design.

Maximum Deformation; The maximum deflection (extrapolated from load-deflection curves) of a theoretical nonlinear sping that is compressed with an infinite load. Under loads equivalent to that of a walking man, the spring travel will be similar to the ground surface deformation when loads are applied.

Surface Roughness: The root mean square of the ground surface elevations. The elevations are measured along the ground surface at 30.48-cm (1-ft) intervals.

Compression Wave Velocity (V_P): Velocity of a compression wave through a medium. Compression waves have the greatest velocity of any elastic wave in the same medium. The motion of the particles is parallel to the direction of propagation. V_P is defined mathematically as

$$V_P = \sqrt{\frac{\lambda + 2G}{\rho}}$$

where

V_P = compression wave velocity, LT^{-1}

λ = Lamé constant, FL^{-2}

G = shear modulus, FL^{-2}

ρ = mass density, $FL^{-4}T^2$

Shear Wave Velocity (V_S): Velocity of a shear wave through a medium. Particle motion is perpendicular to the direction of propagation and is defined mathematically by the equation

$$V_S = \sqrt{\frac{G}{\rho}}$$

where

V_S = shear wave velocity, LT^{-1}

G = shear modulus, FL^{-2}

ρ = mass density, $FL^{-4}T^2$

Bulk Density: The weight (W) of a soil sample per unit of volume (V) of the sample. Symbolically this is

$$\gamma_d = \frac{W}{V} \text{ in g/cm}^3$$

Layer Thickness: Vertical depth (perpendicular to the surface) of soil layers as distinguished by their differing primary wave velocities. The primary wave velocities of the layers are determined by techniques of refraction seismology. (Note: The above-defined layers often, but not necessarily, correspond to soil layers as defined by nonseismic parameters such as grain-size distribution, density, etc.)

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CONVERSION FACTORS, METRIC (SI) TO U. S. CUSTOMARY UNITS OF MEASUREMENT

Metric (SI) units of measurement used in this report can be converted to U. S. customary units as follows:

Multiply	By	To Obtain
Centimeters	0.3937	Inches
Centimeters per second	0.3937	Inches per second
Meters	3.2808	Feet
Meters per second	3.2808	Feet per second
Grams per cubic centimeter	0.0361	Pounds per cubic inch
Kilograms	2.2046	Pounds (mass)
Newtons per meter	0.6849	Pounds (force)per foot

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In accordance with ER 70-2-3, paragraph 6c(1)(b), dated 15 February 1973, a facsimile catalog card in Library of Congress format is reproduced below.

Lundien, Jerry R
Terrain constraints on the design, testing, and deployment of the GATOR mine, by Jerry R. Lundien. Vicksburg, U. S. Army Engineer Waterways Experiment Station, 1976.
vi, 73 p. illus. 27 cm. (U. S. Waterways Experiment Station. Miscellaneous paper M-76-3)
Prepared for Armament Development and Test Center, Air Force Systems Command, Eglin Air Force Base, Fla., under Project No. 2573, Task No. CO, Work Unit No. 001.
References: p. 71-72.

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TA7.W34m no.M-76-3